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SOLAR HEATING SYSTEM PERFORMANCE MONITORING

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Prepared by

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October, 1981

Prepared for

Montana Department of Natural Resources and Conservation
32 South Ewing, Helena, Montana 59620
Renewable Energy and Conservation Program
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THERMAL PERFORMANCE OF THE LEAVENGOOD SOLAR HOUSE

by

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for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM

Grant #RAE-145-800

NOTE ON UNITS

The test results in this report are given in metric or SI units. This convention corresponds to current professional practice and is in accord with the recommendations of the International Solar Energy Society and most technical journals.

Most readers are familiar with the Celsius or Centigrade temperature scale (°C) and with power measured in kilowatts (kW). The metric unit of energy is the Joule (J). Most energy quantities in this report are expressed in megajoules (MJ) which is 10^6 joules or a million joules (1,000 BTU = 1 kBTU = 1.05 MJ). Since one MJ is about one thousand BTU's, a furnace with a rating of 100 thousand BTU/hour would be rated at about 100 MJ/hour. This approximate conversion will be useful to the reader accustomed to thinking in thousands of BTU.

Other abbreviations included in this report are: l = liters, m = meters, m^2 = square meters and kWh = kilowatt hours.

ABSTRACT

This project is located near Bozeman, Montana and is a retrofit to an existing house. The house and the solar system were designed by David Leavengood and Drapes Engineering. The solar system consists of active air collectors combined with rock bin storage housed in a small structure near the residence. A heat pump connects the solar system thermally to the house. The motivation for this design was to combine the solar collector, an efficient producer of low-grade heat, to a heat pump, an efficient user of low-grade heat.

The solar collectors were penalized due to shading from trees on the site which reduced the solar radiation by approximately 40%. The solar heated air available to the heat pump averaged only 3.6 °C above ambient temperatures. Heat losses from the remote building and the lines leading from the heat pump have further reduced the system efficiency. The auxiliary electrical energy consumed to operate the system (heat pump, compressor, fans, etc.) was greater than the solar heat collected. The efficiency of this system would be improved if: (a) the collectors were exposed to more solar radiation and (b) the control system were altered. The average temperature of the house during the monitoring period was 14.9 °C (58.8 °F).

SOLAR COLLECTOR

Type: Active air (with series heat pump)
Manufacturer: Sun Works
Aperture Area: 17.46 m^2 (188 ft^2)
Glazing: Double, glass
Fluid: Air
Flow Rate: 5.83 m^3-min^{-1}
Tilt: 59°
Azimuth: 30° West of South

STORAGE SYSTEM

Material: Rock bin
Volume: 3.99 m^3

AUXILIARY HEAT

Type: Forced air
Manufacturer: Carrier
Fuel: Electric
Capacity: 100 $MJhr^{-1}$
Fireplace: 15 $MJhr^{-1}$

BUILDING

Type: Wood frame, two story
Floor Area: 148 m^2 (1600 ft^2)
Calc. Loss Factor: 1.1 $MJhr^{-1}$ $°C^{-1}$

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1.0 INTRODUCTION

This project is a retrofit of a solar assisted heat pump to an existing residence. The project is located about 20 kilometers north of Bozeman. The house and the solar system were designed by Dave Leavengood and the house is occupied by his family. The system has been operational since December, 1979. Seventy-one days of valid performance data were collected on this system during the winter of 1979-80.

2.0 DESCRIPTION OF HOUSE AND SOLAR SYSTEM

Figure 1 shows a photograph of the solar collectors and the house. The collectors are mounted on a detached building situated about 8 m southwest of the house. The active-air collectors have a total aperture area of 17.5 m^2, a tilt of 59^o and an azimuth of 30^o west of south. The shading diagram in Figure 1 shows that the collectors are shaded until almost noon during the winter season. A tree southwest of the collectors shades the collectors between 3:00 and 4:00 p.m. in the winter. The photograph, taken in the afternoon, also shows the effect of this shading.

The house is a two-story, wood-frame structure having a floor area of 148 m^2, Figures 2 and 3. Auxiliary heat is supplied to the house by an electric furnace and a wood burning fireplace. The heat loss calculations for the Leavengood house are shown in Table 1. The house has an overall loss coefficient of 1.1 $MJhr^{-1}$ $^oC^{-1}$.

Section drawings of the building containing the solar collectors and solar system are shown in Figure 4. The schematic of the solar system shown in Figure 5 is helpful in understanding the operation of this system. When the sun shines on the collector, a differential thermostat simultaneously turns on blower #1 and opens damper #2. When the house thermostat calls for heat, blower #2 and the heat pump are turned on, and damper #1 is opened.

The heat pump is situated in the middle of the floor of the small, attached building, which acts as a plenum chamber, Figure 4. If the solar collectors are operating and the house is not calling for heat, the solar heated air is circulated through the pebble storage located

under the floor. If the solar collectors are operating and the house simultaneously calls for heat, the solar heated air bypasses the pebble bin storage and is circulated by blower #2 directly through the plenum containing the heat pump. If the solar collectors are not operating and the house calls for heat, blower #2 and damper #1 and the heat pump turn on simultaneously and air is circulated through the rock bin storage and the plenum.

Refrigerant circulates from the heat pump through underground insulated pipes to a heat exchanger coil located within the electric auxiliary furnace, Figure 5. There is a two-stage thermostat located in the house. The first stage turns on the furnace fan and the heat pump system and the second stage adds the auxiliary electric coils in the furnace.

The photograph in Figure 6 was taken inside the plenum chamber and shows the heat pump, the collector fan and motorized damper, and the rock bin fan and motorized damper. Figure 7 has photographs of a portion of the auxiliary furnace and shows the wood burning fireplace.

3.0 INSTRUMENTATION LAYOUT AND MEASUREMENTS

The data acquisition system used for monitoring this project is described in Appendix II. The transducer arrangement is shown on the schematic drawing of the solar system and house in Figure 5. Solar radiation was measured by a transducer mounted in the plane of the collectors at the center of the collector array. The ambient air temperature was monitored in a shaded location on the north side of the equipment building.

Temperatures within ducts were measured by a rake of three probes connected to (electrically) average the temperature of the air at that particular station. Air temperatures were measured at the inlet and outlet of the solar collectors and at the inlet and outlet of the rock heat storage bin. Two sets of probes situated at the inlet and outlet of the auxiliary furnace measured the temperature rise of air flowing through the furnace, Figure 7(a). Note that these furnace probes will respond to temperature rises due to the combined effect of the heat pump coil and the auxiliary electric coil. Status relays were connected to the furnace

fan, the collector fan and the rock bin storage fan. Electric power delivered to the furnace coils and to the hot water heater was measured with clamp-on ammeters. The three status relays combined with the auxiliary electric ammeter served to define the mode of operation of the furnace system.

There were two temperature probes in the house to sample room temperature. One probe was located near the furnace thermostat and a second probe was located between the living room and the kitchen. A temperature probe was attached to the outside of the metal chimney from the fireplace. The readings of this probe reflect the intensity of the fire in the fireplace.

Tables 2 and 3 present the Transducer Log and outline the variables measured on site. Note that the data acquisition system was programmed to calculate, on-line; (a) the heat output of the furnace in its various modes, (b) the collector output, (c) the collector efficiency and (d) the rock bin output.

The air flow in the solar collector and furnace system was measured by mapping the cross-section using a hot-wire anemometer, Figure 8. The solar collector duct and rock bin duct were mapped for the two combinations of fan status. These flow measurements were appropriately entered into equations in the on-site DAS as constants. The status switches on fan #1 and fan #2 served to inform the DAS of the appropriate flow constant to use to calculate the heat exchange, for that mode. The collector flow rate was judged adequate for this system. The map of flow through the auxiliary furnace is shown in Figure 9.

4.0 PRESENTATION OF DATA

Efficiency curves of the solar collectors is shown in Figure 10 and compared to a reference curve for this type of collector. The experimental points are seen to be scattered around the expected curve. This scatter is probably related to the shading of the collectors. Since the collectors were only exposed to two to three hours of sun, it was difficult to find periods during which the collectors were at thermal equilibrium.

The hourly raw data from the site was processed and condensed into

the format shown in Table 4. The hourly data for the entire monitoring project is included in Appendix I. Table 4 shows data for January 29, 1980, and will be discussed as an example to explain the calculation procedures.

The first column shows the hour of the day starting at midnight. The second column, SOLAR AVAIL, shows the total solar energy intercepted by the collector array in megajoules. This number is calculated by multiplying the solar flux per unit area by the total area of the solar collector. The second column is the collector output, COLL OUTPUT. The output is calculated by multiplying the temperature difference across the collectors by the flow rate any time the collector fan is on.

Inspection of the data in Table 4 shows that the collector receives little radiation until noon due to the shading discussed previously. Between noon and 1:00 p.m. (1300 hours), the collector turns on and begins delivering heat. The maximum amount of heat is delivered between 2:00 and 3:00 p.m. after which heat output falls off due to the afternoon shading and the reduced solar intensity. The collector is seen to cycle on briefly throughout the evening. We believe this unexpected behavior is due to reverse flow in the solar collector loop due to natural or forced convection through leaking dampers. This reverse flow would warm the thermostat probe in the collector, causing the differential thermostat to turn on the collector fan. Shortly after the fan was turned on, the probe on the collector plate would cool and the fan would turn off. The effect of this cycle is to produce a net, small, negative heat flow out of the system.

The next item, labeled STORE OUTPUT, is solar heat delivered from the storage or the solar collectors directly to the plenum chamber containing the heat pump. The next three columns record heat delivered to the house by the auxiliary furnace. The furnace can operate in three modes: heat pump only, HPUMP ONLY; heat pump and electric, HPUMP &ELECT; and electric only, ELECT ONLY. These heat quantities were all calculated by multiplying the temperature difference across the auxiliary furnace by the mass flow and specific heat of the air. The on-site DAS decides in which category to place the heat, depending on the condition of the status switches.

For comparison, the furnace electrical input, FURN INPUT, is calculated from the reading of the clamp-on ammeter located on the furnace electrical supply. FURN INPUT is shown in a column on the right hand side of the table. During the early morning hours, the house is being heated exclusively by the electric coils in the furnace. Note that the hourly heat flow quantities appearing under ELECT ONLY and the independently measured FURN INPUT agree to within the accuracy of the respective measurements. This agreement adds confidence to our method of measuring the heat pump output of the furnace using the temperature difference and flow measurements on the furnace. The data in Table 4 shows that during the afternoon the heat pump is supplying much of the heat to the house. Comparison of STORE OUTPUT and HPUMP ONLY during the afternoon suggests that some solar heat is being lost due to the envelope losses of the plenum chamber.

Heat output from the fireplace, FIRE PLACE, was calculated using an approximate equation based on the temperature of the fireplace flue probe as compared to the house air temperature. Internal gains due to dissipations from light bulbs & stoves was set at 5.76 MJ per hour. This constant average value was based on readings of the utility meter after furnace, water heater and heat pump power were deducted. The measured dissipation of the electric hot water heater was considered as a heat input to the house and is listed in the column, WATER HEAT.

All of the heat gains from the furnace and from the fireplace and internal electrical dissipation are added together and listed in the column, SUM INPUT. This column can be compared with the next column, labeled HOUSE LOAD, which is calculated by multiplying the calculated load factor in Table 1 by the measured, hourly average temperature difference across the envelope. The comparison of SUM INPUT and HOUSE LOAD provides another test of the reasonableness of the energy data for this project. Transient effects combined with errors in the measurements produce fluctuations in the hourly agreement. These fluctuations normally tend to average out in the daily totals shown at the bottom of the table.

The next six columns show average temperatures of the house and the ambient air along with other temperatures within the solar system.

The column labeled ROOM TEMP is the temperature of the plenum chamber or the room where the heat pump is located. The temperature of this room is seen to get up to almost freezing at 3:00 p.m. due to the solar input on this very cold day.

To move the solar heat from the plenum chamber to the house, electricity must be supplied to the heat pump fan and compressor and to the rock bin fan (blower #2). This electric power is added together and shown near the end of the table, labeled AUX POWER. Comparison of the auxiliary power used by the heat pump, AUX POWER, to the heat pump energy delivered to the house on this day, H.P. OUT, shows that the system consumed approximately twice as much energy as is delivered to the house. The final column, H.P. OUT, is calculated by subtracting FURN INPUT from the sum of the furnace heat outputs. The small numbers, sometimes negative, in this column reflect two things: (a) errors in the measurements and (b) electric power used to run the furnace fan, which appears as a penalty on the heat pump output. If this (pessimistic) number is used, the heat pump output is seen to be only about 1/4 of the auxiliary power put into the heat pump.

The bottom line of this hourly data table shows the totals of all energy quantities and the average of all temperature quantities. On this day, the collectors delivered about 33% of the incident solar radiation to the plenum chamber. The collector auxiliary power, the power to run the electric fan, was about 12 MJ, which gives a coefficient of performance for the collector of 6.0. The data shows that the heat pump (apparently) delivered most of this solar energy to the house. Unfortunately, to move the approximately 70 MJ of solar heat to the house required an investment of 124 MJ of electricity. This results in a system coefficient of performance of less than 0.5. Since an electric resistance heater has a coefficient of performance of 1.0, it is clear that on this day the solar system <u>increased</u> the energy use of the house by about 7%.

The daily average data for the entire monitoring period is shown in Tables 5 and 6. The data is further summarized in Table 7, which focuses on the solar system. The test period covers 71 data days between mid-December and the end of February.

The total solar radiation striking the collector during this period was 8,810 MJ. During the monitoring period, the collector fan absorbed 385 MJ of electricity and the collector delivered 2,563 MJ of solar heat to the plenum chamber and rock storage. The gross collector efficiency is thus 26.9%. If the collector output is reduced by the energy required to run the fan, the net average collector efficiency is 26%. The coefficient of performance of the collector is the solar heat delivered by the collector divided by the electrical energy required to run the fan. For the monitoring period the collector COP was 6.65.

It is estimated that the shading, Figure 1, reduced the solar radiation available to the collectors by at least 40%. The effect of this shading was to severely reduce the collector output, efficiency and coefficient of performance. If this same solar system had been placed at an unshaded location, the collector output would probably have doubled and the coefficient of performance would have been about 10.0.

The auxiliary energy column shows that the electrical power to run the heat pump and its associated fans totaled 10,125 MJ. The solar heat collected during this period was about 2,563 MJ. If we assume that the heat pump delivered all of this heat to the house, the coefficient of performance of the total system is 0.25. This means that the electrical energy would be more efficiently used in the furnace than to run the solar system. This poor performance is partially due to the fact that the room temperature or plenum temperature was only 3.6 °C above ambient temperature during the monitoring period. Inspection of the hourly data in Appendix I shows that quite often the heat pump was reducing the temperature of the plenum room <u>below</u> ambient temperature; a very inefficient mode of operation. These instances are flagged in the Table by a letter "S" appearing on the extreme right of the Table.

Table 8 summarizes the overall performance of the house during the monitoring period. These data show that the fireplace supplied 26% of the heat required. The heat pump was delivering solar heat to the house as well as heat pumped from the atmosphere. From the data in Table 7, it appears that the solar contribution to the total heat load

of the house is less than 10%. This leaves about 65% of the heat supplied to the house by various forms of electrical dissipation.

Tables 9 and 10 show heating degree-day data and monthly utility records of electric power. This data is graphed in Figure 11 and the points on the graph have been identified as "before solar system" and "after solar system". The first observation from this graph is that there is considerable scatter to the points and that the "before" and "after" points are mixed. For reference, two curves are drawn on this graph and labeled "before" and "after". These curves illustrate the trend that would be expected in an ideal test situation <u>if</u> the solar system was contributing 12% toward heating the house. The scatter in these points could be due to changes in living habits; for example, thermostat set points and the extent to which wood heat was used. The data on this graph does not conclusively show a solar contribution.

5.0 F-CHART PERFORMANCE PREDICTION

An f-chart performance analysis was run on the Leavengood system in order to compare some of the measured results with performance predictions. The solar data base used in this analysis is based on measurements made in Bozeman as part of the Solar Insolation Measurement, Montana (SIMM) Program. The solar radiation input used in the analysis was reduced by 40% to account for the shading of the Leavengood collector. No adjustment was made on the temperatures or degree-days. This analysis does not include any beneficial or detrimental effects of the heat exchanger linking the solar system to the house. The analysis assumes a "typical" active air solar system coupled directly to the house. The results of this analysis are shown in Table 11.

The f-chart analysis predicts an annual heat load of 32,867 kWh. This prediction agrees to within a few percent of the actual utility electrical data for 1978 and 1979 shown in Table 10. The f-chart prediction for solar energy added to the house for the months of December, January and February (adjusted for partial months) is 2,500 MJ. The measured collector output during the monitoring period, shown in Table 7, is 2,563 MJ. The average daily solar radiation during the monitoring

period was measured at 1.84 kWh-m^{-2}, the f-chart analysis used an average of 1.67 kWh-m^{-2}. The average ambient temperature measured at the site was -4.5 °C, which is identical to the average ambient temperature used by the f-chart analysis for this period.

These results indicate that the f-chart analysis is quite adequate for predicting the total house load and the collector output, providing the shading of the collector is accounted for. A second run was made with f-chart to determine the solar contribution with no shading. These results showed the 40% reduction in solar radiation on the collectors (due to shading) produced a 60% reduction in solar heat during the monitoring period. The analysis shows that the annual contribution of the shaded collector, <u>if</u> coupled directly to the house, would be 17% of the total heat load. The same collector sited in an unshaded location and <u>coupled directly</u> to the house would contribute 32% of the annual heat load.

TABLE 1

LEAVENGOOD HOUSE HEAT LOAD

	R	U (Btu/hr ft^2 °F)	Area (sq. ft.)	U X A
Ceiling	23	.043	1051	46
*Floor	26	.038	946	36
Walls	14	.071	1882	135
Windows	1.72	0.58	366.4	212
**Infiltration: 16565 ft^3 X $\frac{1}{2}$ X 0.18				149
				578 Btu/hr °F
				or
				1.1 MJ/hr °C

*Crawl space correction: +6

**Assuming $\frac{1}{2}$ air change/hour

TYPES:

S - SOLAR
T - TEMP
DT - DUCT TEMP
ST - STATUS
P - POWER

TABLE 2
TRANSDUCER LOG

LEAVENGOOD HOUSE

DISK #	RS #	PROBE #	TYPE	LOCATION AND MOUNTING
1	1	1	S	Solar Transducer: Mounted on face of collectors
2	2		P	Furnace
3	3		P	Water Heater
Not Saved	5	relay	ST	Furnace Fan Status
Not Saved	6		(ST)	Calc. Element Status
4	7	Hg	ST	Fan #1/Damper #2 Status: Hg switch mounted on armature of Damper #2
5	8	Hg	ST	Fan #2/Damper #1/Heat Pump Status: Hg switch mounted on armature of Damper #1
6	9		C	Furnace - both: Calculated heat output when electric and H.P. are both on
7	10		C	Furnace - only H.P.: Calculated output when only H.P. is on
8	11		C	Furnace - only electric: Calculated output when only electric is on
9	13		C	Collector Output
10	14		C	Collector Efficiency
11	15		C	Rock Bin Output
12	17	20	T	Living Room: Shaded, 2m above floor
12	18	8	T	Rear House: Near thermostat
13	20	36	T	On flue collar of Fireplace
14	25	11	T	1m above heat pump in Equipment Room
15	26	14	T	Beneath Fan #1
Not Saved	29	31	T	Ref. to House
Not Saved	30	21	T	Ref. to Heat Pump

TYPES:

S - SOLAR
T - TEMP
DT - DUCT TEMP
ST - STATUS
P - POWER

TABLE 5
TRANSDUCER LOG
CONTINUED

LEAVENGOOD HOUSE

DISK #	RS #	PROBE #	TYPE	LOCATION AND MOUNTING
16	32	6	T	Ambient: Mounted on north side of Collector Building 2.5m above the ground
17	33	58 69, 70	DT	Furnace In: Averaging set located in return air duct
18	34	60 68, 71	DT	Furnace Out: Averaging set located in hot air duct
19	37	13 17, 18	DT	Into Panels: Averaging set located in the inlet duct to the Collectors at the outlet of Blower #1
20	38	10 67, 72	DT	Out of Panels: Averaging set located in the outlet duct of the Collectors
21	39	59 61, 62	DT	Rock Bin Inlet: Averaging set located in duct from Plenum to Rock Bin
22	40	64 65, 66	DT	Rock Bin Outlet: Averaging set located in duct to Plenum

TABLE 4

SAMPLE HOURLY DATA

DAILY PERFORMANCE SUMMARY FOR THE LEAVENGOOD HOUSE 1/ 29

	SOLAR AVAIL (MJ)	COLL OUTPUT (MJ)	STORE OUTPUT (MJ)	HPUMP ONLY (MJ)	HPUMP &ELECT (MJ)	ELECT ONLY (MJ)	FIRE PLACE (MJ)	WATER HEAT (MJ)	SUM INPUT (MJ)	HOUSE LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	FLUE TEMP (C)	ROOM TEMP (C)	ROCK BIN (C)	ROCK OTLET (C)	FURN INPUT (MJ)	AUX POWER (MJ)	H.P. OUT (MJ)
1	.0	.0	.0	.0	.0	27.1	8.4	2.2	43.4	39.0	12.8	-26.2	-20.8	-11.8	-8.9	-11.1	27.0	.0	.1
2	.0	.0	.0	.0	.0	20.2	7.1	.3	33.4	38.9	12.5	-26.5	-22.3	-12.1	-8.8	-11.3	20.7	.0	-.6
3	.0	.0	.0	.0	.0	19.5	7.2	2.2	34.6	39.5	12.6	-26.9	-22.7	-12.3	-8.8	-11.5	20.0	.0	-.6
4	.0	.0	.0	.0	.0	17.4	9.5	.3	33.0	40.0	13.0	-27.0	-20.5	-12.2	-8.7	-11.5	17.0	.0	.4
5	.0	.0	.0	.0	.0	31.1	12.5	.3	49.6	40.4	13.6	-26.8	-17.3	-11.9	-8.7	-11.4	31.3	.0	-.2
6	.0	.0	.0	.0	.0	33.6	12.3	2.3	54.1	41.1	13.2	-27.9	-18.5	-12.0	-8.6	-11.4	34.4	.0	-.5
7	.0	.0	.0	.0	.0	15.4	14.3	.2	35.7	40.3	12.2	-28.1	-16.9	-11.9	-8.6	-11.3	16.9	.0	-1.5
8	.0	.0	.0	.0	.0	20.0	12.4	2.1	40.3	40.5	13.3	-27.3	-17.8	-12.1	-8.5	-11.4	20.1	.0	-.1
9	1.3	.0	.0	.0	.0	42.5	11.4	.6	60.3	41.7	14.4	-27.3	-18.9	-12.1	-8.5	-11.4	44.8	.0	-2.3
10	3.8	.0	.0	.0	.0	37.9	11.3	4.1	59.1	40.5	16.5	-24.0	-15.7	-11.9	-8.4	-11.4	37.8	.0	.2
11	10.7	.0	.9	4.6	3.0	.0	12.5	.4	26.2	36.2	13.7	-22.6	-13.1	-11.8	-8.7	-10.7	8.2	12.6	-.6
12	7.5	.0	3.6	7.7	1.6	.0	10.9	.2	26.2	35.3	13.8	-21.5	-13.6	-15.6	-11.4	-11.2	6.0	14.4	3.3
13	42.7	10.4	8.8	8.6	1.7	.0	14.3	.3	30.6	33.5	13.9	-19.6	-8.3	-11.3	-9.7	-4.2	5.0	15.1	5.2
14	70.4	21.3	14.6	9.4	1.8	.0	13.2	.3	30.5	32.6	14.3	-18.4	-8.1	-4.7	-8.2	6.8	5.5	16.1	5.7
15	66.6	24.2	15.2	10.0	1.4	.0	8.4	9.0	34.5	32.6	14.8	-17.9	-12.5	-.9	-6.5	11.1	4.8	16.8	6.6
16	13.8	15.9	9.8	7.7	.0	.0	7.5	11.1	32.0	32.0	15.3	-16.7	-12.1	-.4	-4.9	8.1	1.9	14.5	5.8
17	3.1	6.6	5.7	5.1	.0	.0	8.4	11.0	30.2	35.1	15.2	-19.9	-14.5	-3.9	-4.3	2.3	1.3	9.1	3.9
18	.0	1.1	5.3	8.5	1.6	.0	9.6	10.8	36.2	36.0	15.2	-22.9	-16.3	-8.9	-4.4	-4.4	5.4	15.3	4.6
19	.0	-.3	3.5	5.3	.8	18.1	10.4	8.9	49.2	36.9	15.8	-23.1	-15.7	-10.5	-5.6	-8.4	22.8	9.7	1.4
20	.0	-1.3	.0	.0	.0	16.1	11.0	4.8	37.6	39.4	15.1	-23.3	-15.3	-7.9	-5.3	-8.9	16.3	.0	-.2
21	.0	-1.2	.0	.0	.0	10.1	12.1	5.7	33.7	37.2	14.0	-23.2	-14.0	-8.6	-6.1	-9.4	11.8	.0	-1.7
22	.0	-1.2	.0	.0	.0	25.2	10.4	10.8	52.2	39.5	16.3	-23.3	-15.8	-9.1	-6.7	-9.8	25.7	.0	-.4
23	.0	-1.2	.0	.0	.0	.0	16.1	.9	22.7	36.5	13.0	-23.5	-10.4	-9.3	-7.0	-10.2	.1	.0	-.1
0	.0	-.8	.0	.0	.0	18.0	15.8	2.2	41.8	33.7	12.4	-21.3	-8.5	-9.6	-7.1	-10.4	19.0	.0	-1.0
	220.0	73.5	67.4	66.9	11.9	352.2	257.0	90.9	927.0	902.4	14.1	-23.5	-15.4	-9.7	-7.6	-7.2	403.7	123.6	27.2

COLLECTOR AUX POWER = 11.991035

TABLE 5
DAILY SUMMARY DATA

December 1979

DA	SOLAR AVAIL (MJ)	COLL OUTPUT (MJ)	STORE OUTPUT (MJ)	HPUMP ONLY (MJ)	HPUMP &ELECT (MJ)	ELECT ONLY (MJ)	FIRE PLACE (MJ)	WATER HEAT (MJ)	SUN INPUT (MJ)	HOUSE LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	FLUE TEMP (C)	ROOM TEMP (C)	ROCK BIN (C)	ROCK OTLET (C)	FURN INPUT (MJ-	AUX POWER (MJ)	HEAT PUMP (MJ)
14	.0	.0	3.8	.0	10.2	2.0	.0	.5	53.0	92.9	17.3	4.0	5.2	13.4	9.4	19.8	15.8	11.1	-3.7
15	20.1	-1.0	8.4	.1	164.4	13.6	139.7	1.7	448.7	633.1	16.3	-10.1	-4.7	9.1	8.4	10.3	231.2	160.3	-53.2
16	145.8	39.4	8.3	.1	125.8	11.0	405.5	1.7	655.3	597.5	15.8	-9.1	4.9	7.5	6.8	8.7	179.3	121.8	-42.5
17	32.1	.0	1.8	.1	66.4	15.0	29.9	1.7	251.4	235.7	15.8	5.9	7.4	9.7	9.4	9.7	104.1	64.5	-22.6
18	162.8	65.9	7.3	1.1	6.6	41.0	7.0	30.6	224.5	224.6	17.1	7.7	8.0	12.6	9.3	13.4	66.0	10.8	-17.3
19	39.0	6.5	25.7	16.6	39.4	.7	72.8	44.3	306.4	270.9	15.8	4.0	7.1	8.6	8.3	14.0	62.6	52.6	-5.9
20	62.9	8.9	15.8	20.1	17.8	.3	63.5	39.4	279.3	282.8	14.0	2.2	5.1	6.4	6.4	8.6	35.2	47.8	5.0
21	126.3	37.3	49.3	63.3	9.0	.7	41.0	25.7	278.0	317.5	12.6	-.7	1.9	2.9	3.9	8.2	40.2	135.3	32.8
22	45.9	.0	32.0	75.2	17.1	.6	30.7	17.9	279.7	346.2	12.4	-2.0	.4	-1.4	1.3	1.8	59.6	164.0	32.3
23	183.5	35.3	46.5	81.1	19.3	.4	101.2	20.2	350.5	395.3	12.4	-4.1	-.8	-2.6	-.5	1.3	65.8	174.1	34.0
24	156.5	42.8	46.2	77.6	18.2	.1	.0	18.0	252.1	311.6	12.5	-.5	.7	-2.0	-.7	2.2	65.6	166.7	32.2
25	23.9	.0	19.9	69.2	18.6	.1	.0	18.4	244.6	300.4	12.5	-.0	.8	-3.4	-.6	-1.6	62.9	155.2	25.1
26	107.4	29.4	41.6	81.4	20.5	.1	.0	19.3	259.6	359.5	12.4	-2.6	-1.1	-3.8	-1.8	-.7	70.8	177.8	31.2
27	190.5	62.7	65.9	92.0	51.4	.1	6.3	19.7	307.8	441.0	12.4	-5.9	-4.3	-3.1	-2.0	1.6	119.2	205.8	24.3
28	198.0	62.5	36.2	50.6	116.2	.0	47.9	37.4	390.3	512.3	13.6	-7.7	-5.4	-3.1	-3.1	-.5	179.8	132.5	-13.0
29	196.7	55.0	57.4	61.8	188.5	.0	66.3	37.3	492.1	555.0	16.9	-6.6	-4.0	-2.9	-1.3	-.1	263.9	173.8	-13.6
30	196.1	63.9	49.9	55.8	147.0	.6	26.5	30.3	403.5	507.8	16.0	-5.2	-3.0	-2.3	-1.9	1.0	216.4	156.2	-7.9
31	55.3	13.6	47.2	57.2	43.9	.0	.0	50.3	283.9	311.0	12.4	-1.2	.0	-.2	1.4	5.1	85.1	141.1	15.0

January 1980

DA	SOLAR AVAIL (MJ)	COLL OUTPUT (MJ)	STORE OUTPUT (MJ)	HPUMP ONLY (MJ)	HPUMP &ELECT (MJ)	ELECT ONLY (MJ)	FIRE PLACE (MJ)	WATER HEAT (MJ)	SUN INPUT (MJ)	HOUSE LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	FLUE TEMP (C)	ROOM TEMP (C)	ROCK BIN (C)	ROCK OTLET (C)	FURN INPUT (MJ)	AUX POWER (MJ)	HEAT PUMP (MJ)
1	35.2	.0	11.3	50.7	62.6	.1	.0	72.2	329.6	387.0	14.7	-.8	.7	-1.5	.8	-.2	114.5	137.2	-1.1
2	184.2	52.0	38.4	52.9	38.0	.0	191.8	55.2	476.1	405.5	15.0	-2.0	5.9	.3	.9	3.8	89.3	135.7	10.6
3	53.4	7.3	27.4	46.9	65.4	.7	120.3	50.9	422.3	407.3	14.8	-2.1	2.2	-1.1	.7	1.5	110.7	125.9	2.3
4	55.9	12.6	37.2	60.7	85.8	.1	148.2	71.4	595.5	469.4	15.1	-4.4	1.3	-5.7	-3.1	-3.0	154.0	163.5	-6.4
5	13.8	.0	2.7	46.5	31.5	.4	150.6	91.8	457.0	429.3	14.7	-3.2	1.8	-1.6	-.7	-2.1	85.6	110.3	12.7
6	208.1	56.5	95.4	139.0	81.6	51.6	278.0	27.4	717.9	808.2	13.5	-20.2	-11.6	-8.6	-6.3	-4.2	240.0	280.4	32.2
7	110.6	.0	30.9	104.3	103.1	36.4	197.0	67.3	648.3	727.3	15.1	-15.2	-10.0	-11.3	-8.5	-9.6	228.7	235.7	15.1
8	6.3	.0	17.1	49.6	69.6	95.0	132.1	20.6	441.8	475.1	14.2	-22.4	-17.3	-12.1	-9.0	-10.1	222.0	121.0	-7.9
9	60.3	17.5	42.3	45.0	41.3	91.1	94.0	45.3	426.2	324.9	12.8	-4.3	-3.2	-8.4	-6.2	-7.2	164.2	92.8	13.3
10	6.3	3.4	42.8	105.9	90.4	15.5	99.5	48.4	497.0	559.7	15.4	-8.4	-5.0	-9.7	-6.3	-7.8	191.9	235.1	20.9
11	54.1	13.6	39.9	94.3	111.1	.9	113.6	48.8	501.2	557.2	14.8	-9.9	-6.2	-10.4	-7.9	-8.3	200.2	216.5	6.2
12	30.2	20.7	12.1	35.5	45.5	1.7	12.8	69.9	303.5	295.0	14.8	2.6	2.8	-2.6	-3.1	-2.1	80.1	87.4	2.5
13	40.2	7.6	9.1	21.7	37.4	.9	188.1	64.3	450.6	297.3	15.4	3.0	9.7	1.1	1.0	1.1	61.0	55.9	-1.0
14	153.4	52.8	21.4	23.3	37.0	.3	128.5	43.7	371.2	285.0	15.0	3.1	7.4	3.4	3.0	5.6	55.8	60.5	3.9
15	24.5	.0	26.2	39.1	71.2	1.3	44.9	45.0	339.8	377.9	14.6	-1.1	1.4	.7	1.8	3.5	112.8	107.2	-1.1
16	178.5	55.9	32.3	51.2	65.1	.9	110.9	60.0	427.3	441.9	14.4	-4.0	.3	-1.3	-.8	2.4	117.6	134.0	.6
17	69.8	15.2	41.1	72.2	64.1	.2	87.5	64.6	426.8	409.2	15.4	-1.6	1.4	-1.8	-.0	1.4	120.2	178.1	16.3
18	42.1	.0	36.7	85.9	100.4	.7	202.4	43.2	570.9	620.1	15.7	-10.1	-4.7	-6.3	-4.0	-4.3	185.0	209.7	2.0
19	206.2	63.7	67.9	100.6	61.9	44.7	219.1	47.7	606.5	674.7	14.5	-14.8	-8.0	-7.2	-6.4	-3.3	177.6	214.5	27.6
20	143.9	44.7	52.0	75.1	39.8	89.4	254.6	50.9	648.2	590.5	14.5	-10.1	-2.5	-5.8	-4.6	-2.6	182.9	164.6	21.5
21	131.4	35.8	36.5	57.8	81.7	.9	155.9	39.9	474.4	480.8	14.5	-5.5	-1.2	-3.7	-2.8	-1.4	145.0	155.1	-4.6
22	147.1	44.3	55.7	79.0	81.7	.0	201.7	32.9	533.6	481.9	14.4	-5.7	-.3	-4.6	-3.4	-1.5	151.7	194.9	9.1
23	171.0	56.7	14.6	40.8	46.6	.1	50.1	61.7	337.5	321.4	12.9	-.4	1.8	-1.3	-.5	-.4	83.2	105.9	-.8
24	25.1	.0	59.7	83.9	145.3	2.6	97.8	21.1	477.5	550.8	10.7	-14.4	-10.5	-4.1	-1.8	1.1	246.1	223.7	-14.3
28	154.0	68.8	53.2	34.7	19.7	138.8	85.1	44.1	385.7	423.6	14.8	-23.7	-17.8	-8.4	-8.5	-4.4	180.1	65.5	15.1
27	220.0	73.5	67.4	65.9	11.9	352.2	267.0	90.9	927.0	902.4	14.1	-23.5	-15.4	-9.7	-7.6	-7.2	403.7	193.6	27.0
30	210.6	76.4	34.6	34.1	44.6	265.7	290.2	48.6	815.7	721.2	15.1	-16.3	-6.6	-6.2	-6.4	-4.1	300.2	50.0	-5.8
31	191.1	64.5	88.6	102.4	63.3	.3	204.4	52.2	554.3	539.7	15.7	-8.8	-2.4	-6.1	-5.7	-.5	131.7	215.9	39.3

TABLE 6
DAILY SUMMARY DATA

February 1980

DA	SOLAR AVAIL (MJ)	COLL OUTPUT (MJ)	STORE OUTPUT (MJ)	HPUMP ONLY (MJ)	HPUMP &ELECT (MJ)	ELECT ONLY (MJ)	FIRE PLACE (MJ)	WATER HEAT (MJ)	SUM INPUT (MJ)	HOUSE LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	FLUE TEMP (C)	ROOM TEMP (C)	ROCK BIN (C)	ROCK OTLET (C)	FURN INPUT (MJ)	AUX POWER (MJ)	HEAT PUMP (MJ)
1	87.9	32.6	41.8	70.0	75.9	9.2	12.8	34.0	345.9	376.8	15.4	.4	2.1	-4.6	-3.9	-2.0	148.1	180.4	7.1
2	88.6	27.6	28.7	48.3	47.7	.6	50.3	50.8	335.9	302.8	15.2	2.5	5.0	-1.5	-1.4	-.3	87.1	126.4	7.5
3	70.4	21.7	11.4	19.1	53.5	.1	176.4	25.1	412.5	325.0	16.0	2.4	8.6	.3	-.4	.6	82.9	62.8	-10.2
4	143.9	47.6	54.6	57.5	67.5	.8	6.2	69.0	339.2	397.8	15.6	-1.0	.8	.9	.9	4.3	117.1	152.5	8.7
5	182.3	60.8	61.6	63.8	78.8	.1	98.5	42.7	422.2	444.7	15.0	-3.6	-.1	.1	.5	3.8	135.5	170.0	7.3
6	42.7	-1.2	24.3	59.6	67.0	.9	12.3	83.1	351.2	406.4	15.6	-1.3	.4	-2.6	-.6	-1.1	123.9	155.6	3.6
7	135.8	22.2	40.1	64.6	77.6	1.4	80.0	32.7	374.6	486.4	15.3	-4.9	-.9	-3.7	-2.7	-1.8	135.2	167.1	8.4
8	252.1	83.0	85.2	93.5	77.6	1.1	119.9	56.6	486.9	531.3	15.2	-6.9	-3.1	-3.5	-3.6	.9	148.0	217.0	24.2
9	199.9	64.4	57.6	79.0	62.3	.7	199.6	50.5	530.4	510.8	15.5	-5.8	1.3	-2.1	-1.9	1.7	123.4	192.5	18.7
10	93.7	25.6	52.8	104.8	44.0	.1	234.0	47.3	563.4	519.8	15.8	-5.8	1.2	-4.4	-2.3	-1.4	115.9	232.3	32.9
11	193.0	66.5	65.3	96.0	37.9	.1	145.6	73.0	490.9	487.4	15.7	-4.6	-.6	-3.6	-3.2	-.0	98.3	215.3	35.7
12	71.7	11.1	39.9	96.2	70.1	1.2	31.3	76.8	413.8	512.0	15.8	-5.5	-3.0	-6.0	-3.4	-3.8	140.7	222.8	26.8
13	66.0	-.7	35.5	95.6	108.3	64.4	143.0	61.7	611.2	683.0	15.6	-12.9	-8.3	-8.8	-6.4	-6.8	253.9	227.9	11.4
14	108.7	7.2	15.8	26.3	32.6	374.2	290.9	69.1	931.4	852.8	15.5	-21.3	-12.2	-8.6	-7.2	-7.8	431.3	64.6	1.8
15	118.8	16.8	32.8	57.1	113.6	330.5	270.3	51.6	961.2	922.2	17.0	-21.4	-12.5	-11.4	-9.8	-7.7	519.8	148.8	-18.6
16	289.8	93.2	54.7	39.1	55.7	132.0	399.8	79.6	844.5	648.9	16.5	-10.5	3.1	-4.3	-5.6	-.7	222.0	105.0	4.9
17	84.9	32.0	42.8	66.3	71.7	.8	146.0	40.9	463.9	385.8	16.6	.6	5.2	-1.3	-.7	1.7	125.4	167.2	13.4
18	159.0	61.5	24.8	34.6	31.4	.1	14.2	72.3	290.7	310.2	16.4	3.5	5.5	2.6	1.7	4.7	56.4	87.7	9.6
19	255.8	93.8	18.3	11.5	53.0	4.0	44.2	104.5	355.5	284.5	16.4	4.6	6.4	7.1	4.9	10.5	77.5	48.0	-9.0
20	84.9	9.0	37.1	40.1	36.3	.1	84.6	47.6	346.9	347.7	16.0	1.5	5.3	6.4	6.0	12.3	61.7	103.5	14.9
21	269.0	88.8	48.8	38.3	54.2	1.9	185.1	76.7	494.4	381.2	16.3	.4	6.1	5.6	3.6	10.1	85.2	106.4	6.2
22	206.8	59.2	64.9	57.1	55.6	.9	126.3	41.1	419.2	404.7	15.9	-.9	3.0	6.2	5.1	12.5	92.7	148.7	20.9
23	305.5	95.3	44.9	28.6	63.3	.0	63.7	71.6	370.4	417.5	16.0	-1.4	1.4	5.8	3.9	9.9	100.3	95.1	-3.4
24	316.2	97.4	52.2	39.1	76.9	2.6	190.6	57.0	504.5	422.5	14.8	-2.8	3.7	6.8	5.5	13.2	116.6	114.9	2.0
25	257.1	74.9	61.9	45.3	40.9	.3	69.9	46.5	295.0	255.9	15.1	-.9	2.9	5.7	4.5	14.1	68.5	114.9	17.9

March 1980

DA	SOLAR AVAIL (MJ)	COLL OUTPUT (MJ)	STORE OUTPUT (MJ)	HPUMP ONLY (MJ)	HPUMP &ELECT (MJ)	ELECT ONLY (MJ)	FIRE PLACE (MJ)	WATER HEAT (MJ)	SUM INPUT (MJ)	HOUSE LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	FLUE TEMP (C)	ROOM TEMP (C)	ROCK BIN (C)	ROCK OTLET (C)	FURN INPUT (MJ)	AUX POWER (MJ)	HEAT PUMP (MJ)
3	.0	.5	4.8	8.8	9.3	49.4	29.0	15.2	146.3	181.8	16.7	-13.6	-9.9	.0	1.4	2.7	70.3	26.2	-2.7
4	86.1	.0	45.1	55.9	111.0	283.3	57.0	60.6	706.0	811.4	16.3	-17.5	-14.5	-5.3	-2.1	-1.0	440.0	145.5	10.1
5	79.2	.0	9.9	24.9	28.3	292.9	201.9	74.6	760.8	723.7	14.7	-15.4	-8.8	-5.5	-4.7	-5.1	334.3	56.7	11.8
6	209.3	72.5	58.1	60.2	24.0	171.2	250.6	32.8	677.1	526.6	15.4	-6.6	.9	-1.7	-2.7	.1	216.5	125.4	39.0
7	200.5	63.4	57.4	72.4	26.5	86.7	79.6	59.3	462.7	469.2	16.2	-3.4	-.6	.4	-.4	2.9	145.4	157.0	40.1
8	111.3	30.4	55.0	106.0	64.7	40.7	.0	77.4	427.0	464.9	16.9	-2.5	-.8	-3.3	-1.3	-.6	169.6	237.0	41.8
9	94.3	34.2	25.0	38.4	57.9	69.7	.0	63.5	367.8	402.5	17.1	.3	2.1	-.9	-1.4	-.1	157.2	100.1	8.3
10	11.3	5.7	6.5	15.5	3.1	43.5	.0	16.0	135.6	140.6	15.3	1.2	2.3	1.2	.7	1.0	52.7	34.2	9.3

TABLE 7

OVERALL PERFORMANCE SUMMARY FOR LEAVENGOOD SOLAR COLLECTORS

Month	Days	Solar Avail. MJ	Collector Output MJ	Storage Output MJ	Collect. Aux. Energy MJ	Aux. Energy MJ	Ambient Temp. °C	Room Temp. °C	Rock Bin °C
December	18	1944	522	563	60	2255	-1.8	2.5	2.9
January	28	2778	849	981	164	4242	-8	-4.3	-3.0
February	25	4088	1192	1101	161	3628	-3.8	-.8	-.7
Total	71	8810	2563	2645	385	10125	-4.5	-.9	-.3

Average Collector Efficiency: 26.9% Gross
26% Net

Collector Coefficient of Performance $= \frac{2563}{385} = 6.65$

System Coefficient of Performance $= \frac{2563}{10125} = 0.25$ (Assuming all collected solar heat reached house.

TABLE 8

OVERALL HEAT SUMMARY FOR THE LEAVENGOOD HOUSE

Month	Days	*Heat Pump Only	*Furnace and Heat Pump	Furnace Only	Elec. Dissip.	Fireplace	Water Heater	Total Input	Calculated Heat	House Temp.	Ambient Temp.
		MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ	°C	°C
December	18	806	1081	86	2384	1032	412	5801	6707	14.3	-1.8
January	28	1802	1805	1193	3732	4126	1419	14077	13986	14.5	-8
February	25	1132	1627	927	3643	3196	1464	11989	11649	15.8	-3.8
	—	—	—	—	—	—	—	—	—	—	—
Total	71	3740	4513	2206	9739	8354	3295	31867	32342	14.9	4.5
Distribution		*12%	*14%	7%	31%	26%	10%	100%			

* Note: These items include solar heat and heat pumped from atmosphere

TABLE 9

BOZEMAN DEGREE DAY DATA

(Degrees Celsius)

Month	Long-Term Average	1978		1979	
		Degree Days	Ratio	Degree Days	Ratio
January	762	733	.96	999	1.31
February	614	597	.97	618	1.00
March	596	473	.79	546	.92
April	377	330	.87	377	1.00
May	238	261	1.11	230	.97
June	128	99	.77	93	.73
July	25	32	1.28	11	.44
August	38	46	1.21	22	.58
September	160	142	.89	58	.36
October	322	285	.88	261	.81
November	542	705	1.30	606	1.12
December	682	825	1.20	550	.81
TOTAL	4484	4528	1.01	4371	.97

TABLE 10

MONTHLY UTILITY RECORDS OF ELECTRIC POWER

	1978 kWh	1979 kWh	1980 kWh
January	5408	6656	3441
February	4576	4823	4210
March	3919	3963	2801
April	2304	2949	2047
May	2079	2396	1050
June	1780	1232	1126
July	1093	980	1145
August	1145	1092	
September	1432	1054	
October	1884	1131	
November	3040	3061	
December	5347	3620	

TABLE 11

F-CHART PREDICTION OF PERFORMANCE

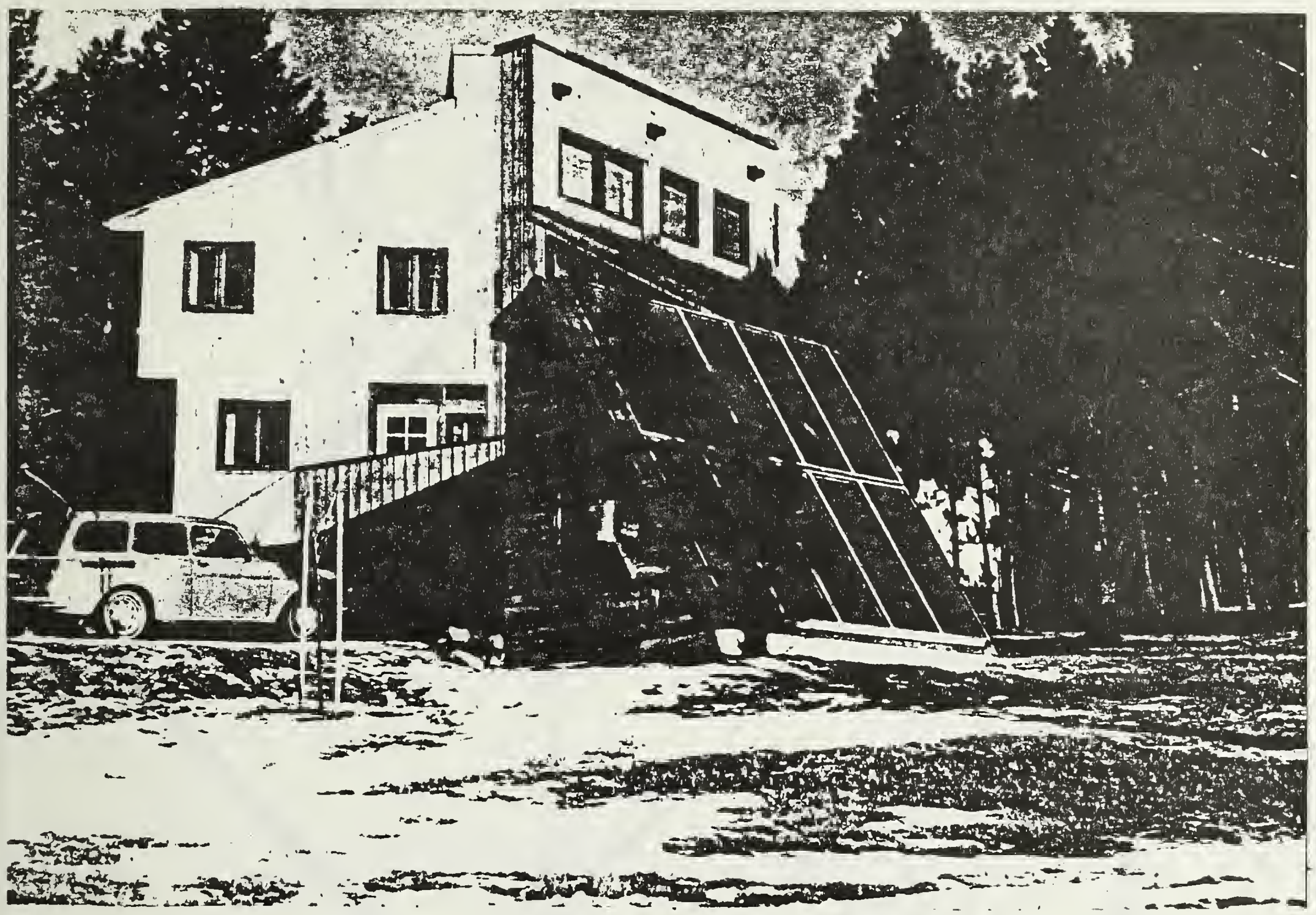
MON	----DAILY----		----------			MONTHLY			----------
	*SOLAR RAD KWH/m2	AMBT TEMP (C)	DEGREE DAYS (C-DAY)	WATER LOAD KWH	HEAT LOAD KWH	TOTAL LOAD KWH	SOLAR FRAC (%)	SOLAR ENERGY KWH	BACKUP ENERGY KWH
JAN	1.7	-6.4	762	0	5579	5579	5	279	5300
FEB	2.0	-3.4	614	0	4498	4498	9	392	4106
MAR	2.6	-1.0	597	0	4368	4368	14	628	3740
APR	2.8	5.6	378	0	2765	2765	25	690	2075
MAY	2.4	10.5	238	0	1745	1745	32	559	1186
JUN	2.7	14.2	129	0	943	943	74	695	248
JUL	2.9	19.1	25	0	183	183	100	183	0
AUG	2.9	18.3	39	0	285	285	100	284	1
SEP	2.9	13.1	160	0	1171	1171	64	754	417
OCT	2.7	7.8	323	0	2363	2363	29	676	1687
NOV	1.7	.1	542	0	3969	3969	8	299	3670
DEC	1.3	-3.8	683	0	4998	4998	3	141	4857
YEAR	2.4	6.2	4490	0	32867	32867	17	5580	27287

*Reduced by 40% to account for shading

YEARLY SOLAR FRACTION.... .17

CLIENT.................... LEAVENGOOD
LOCATION.................. BOZEMAN

COLLECTOR AREA........... 18.58 m2, 179.9 ft2
COLLECTOR TILT........... 60 DEGREES
COLLECTOR TYPE........... AIR
EFFICIENCY SLOPE......... 3.50 W/C-m2, .61 BTU/F-ft2
Y-INTERCEPT.............. .61
HOUSE LOAD FACTOR........ .31 KWH/C-HOUR, 578 BTU/F-HOUR



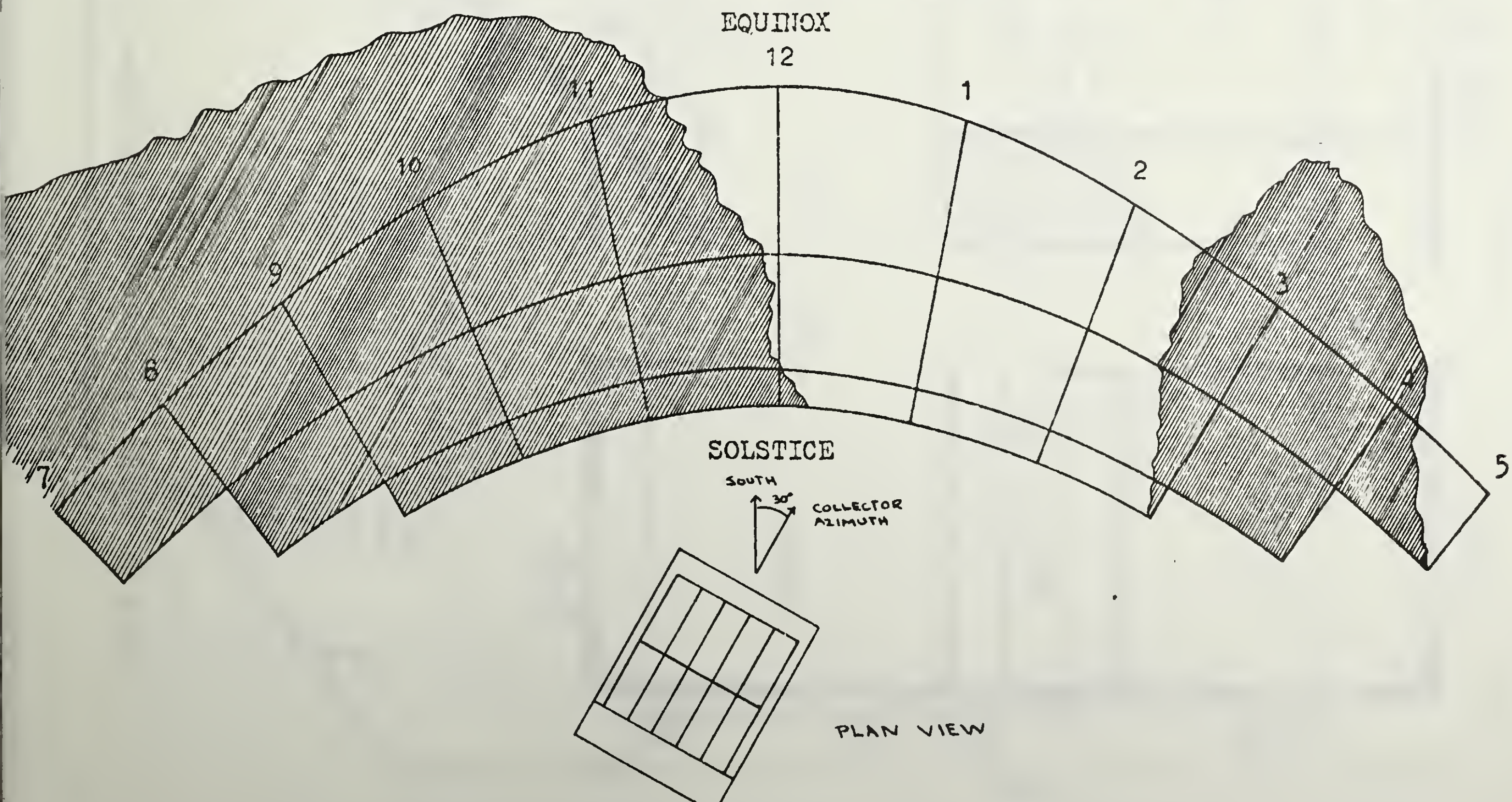
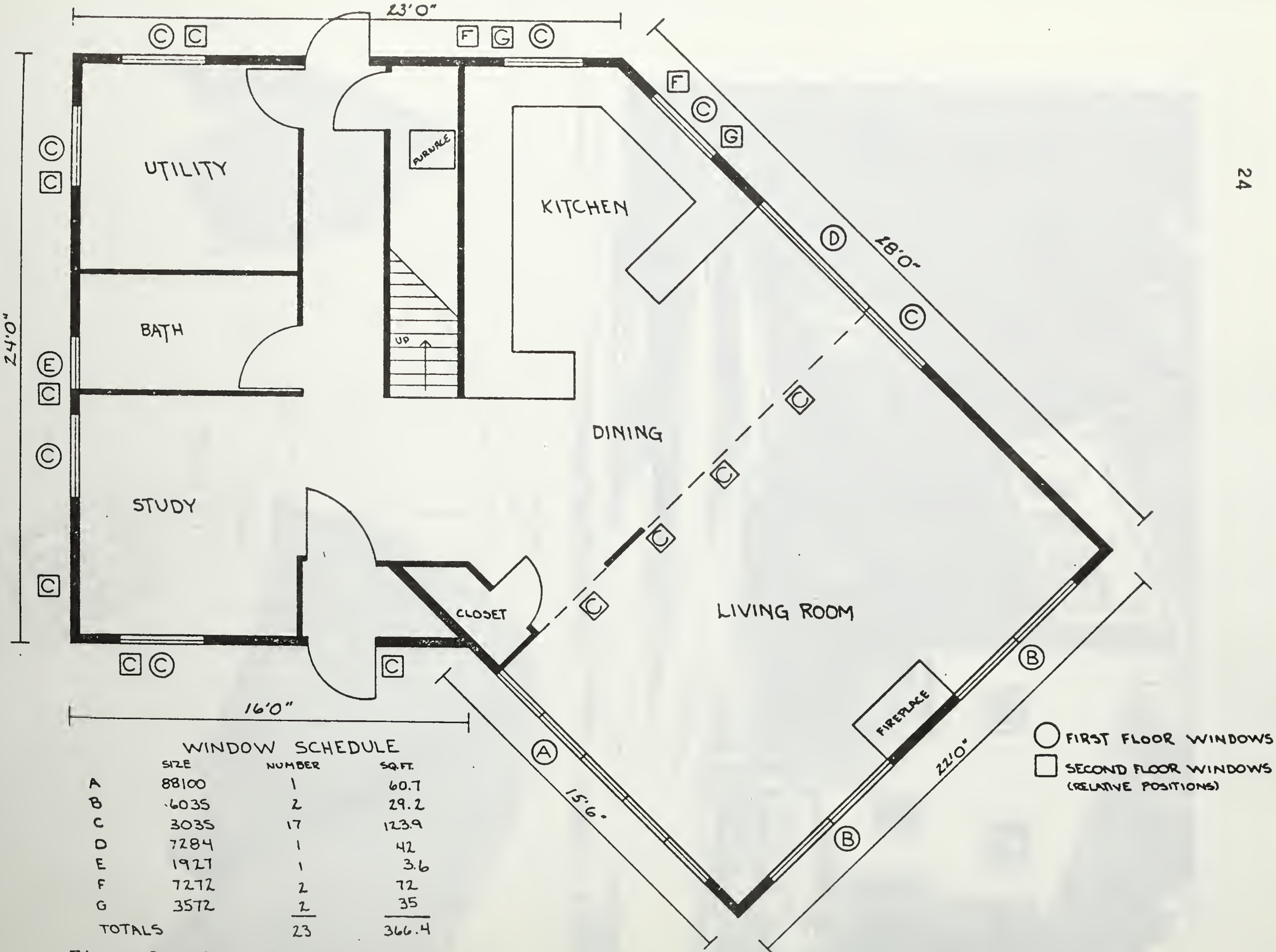


Figure 1: Photograph of Leavengood Solar System and Shading Diagram



WINDOW SCHEDULE

	SIZE	NUMBER	SQ.FT.
A	88100	1	60.7
B	·6035	2	29.2
C	3035	17	123.9
D	7284	1	42
E	1927	1	3.6
F	7272	2	72
G	3572	2	35
TOTALS		23	366.4

Figure 2: Floor Plan of Leavengood House

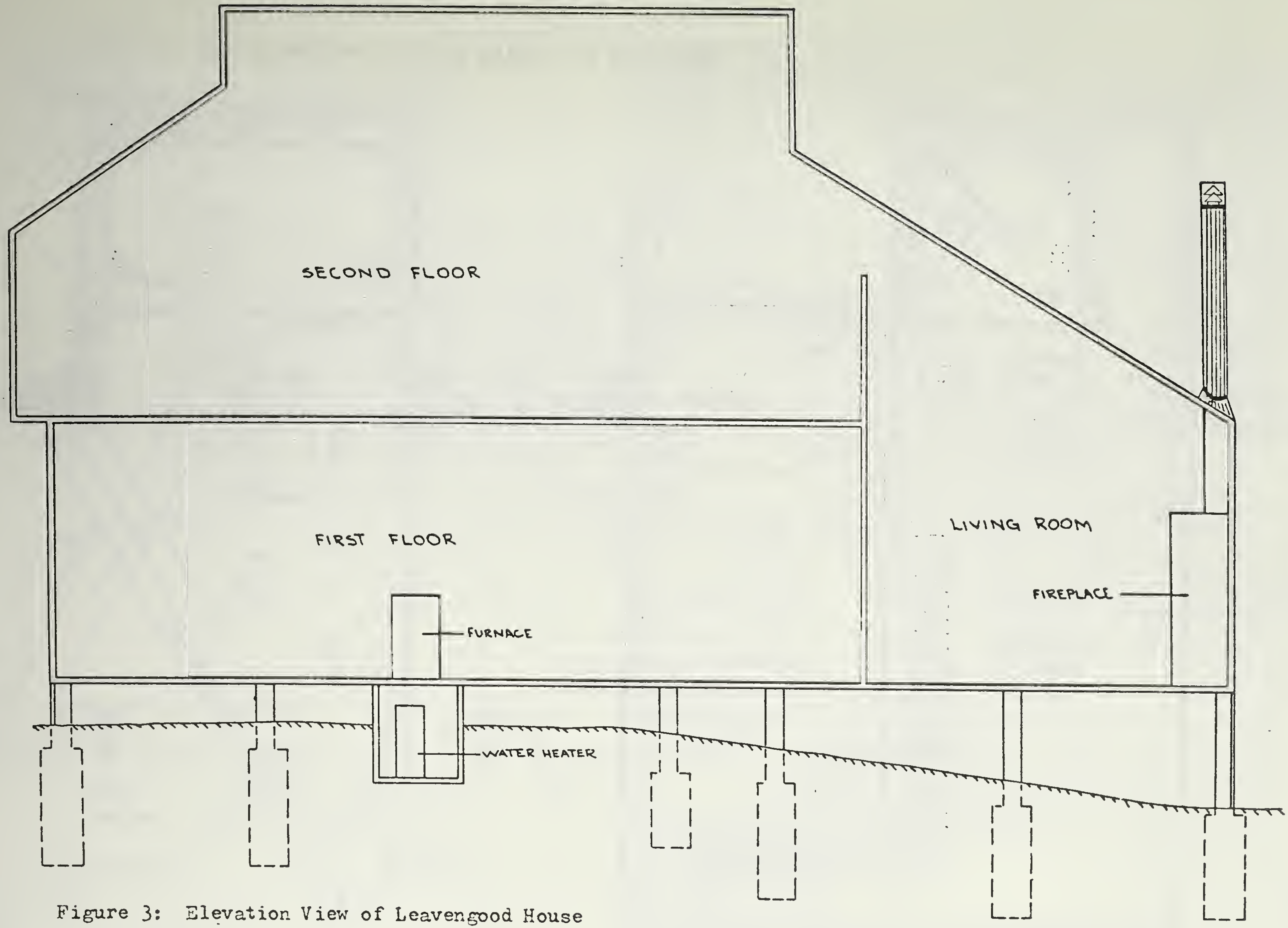


Figure 3: Elevation View of Leavengood House

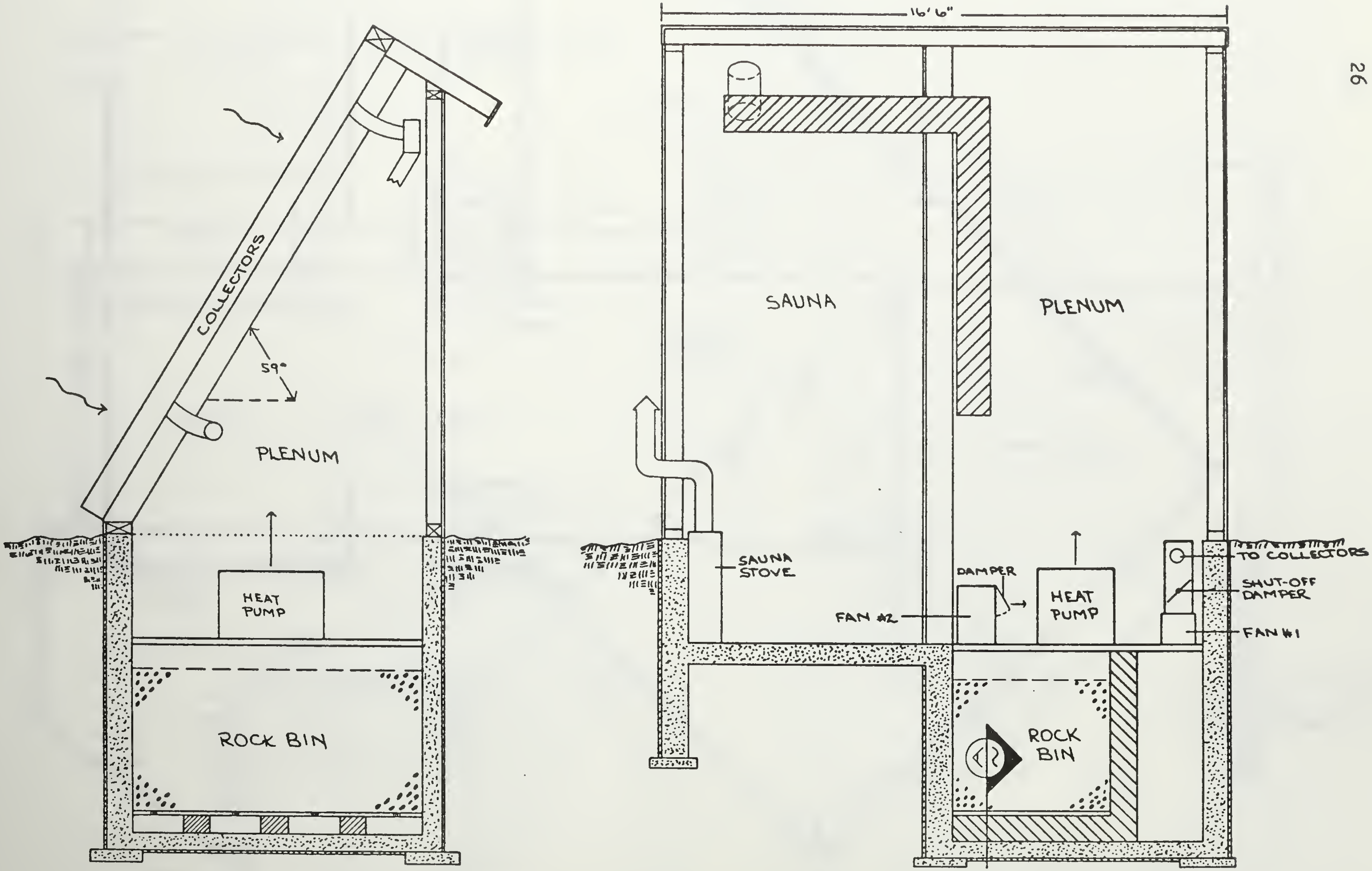


Figure 4: Elevation View of Solar System and Heat Pump

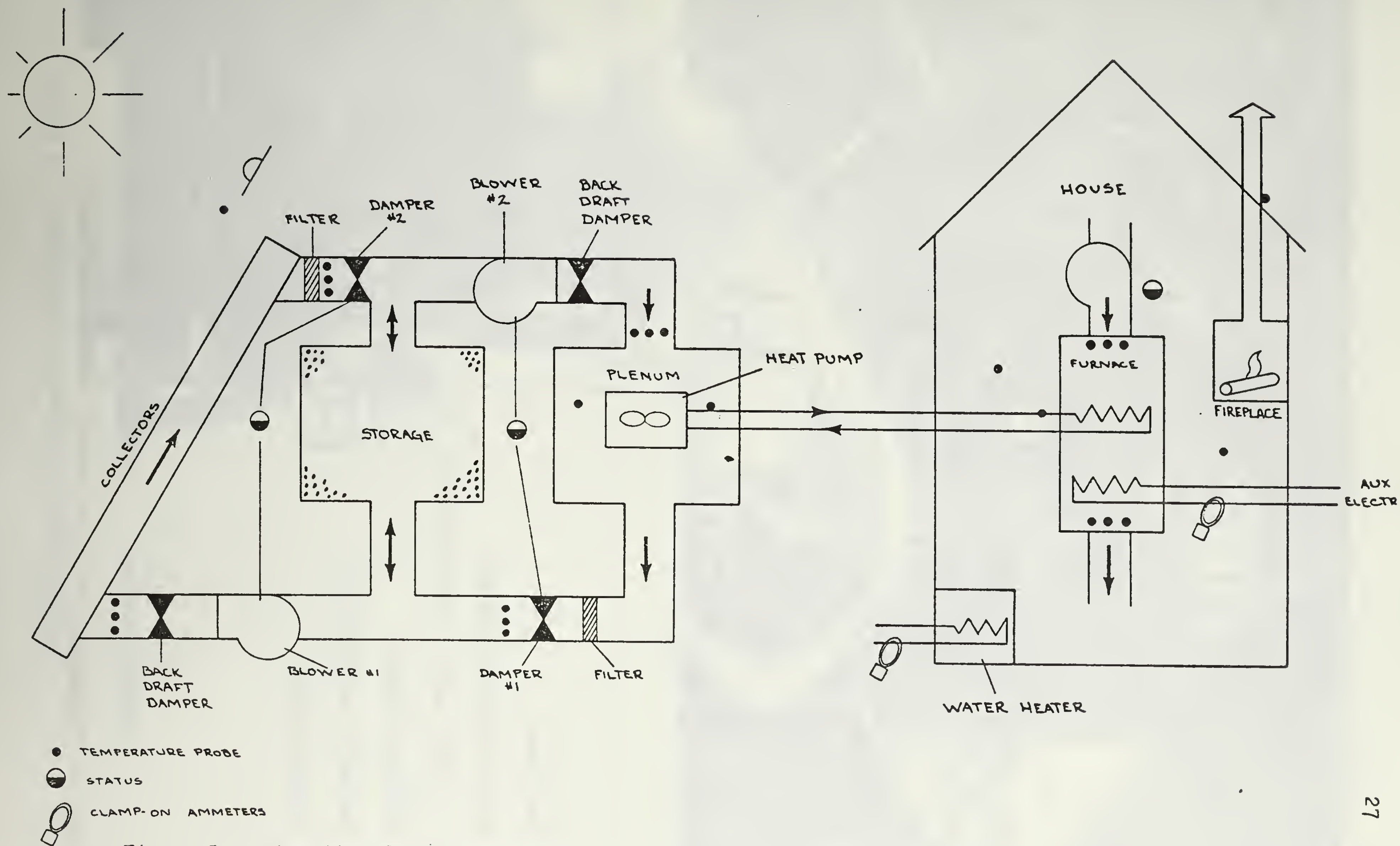
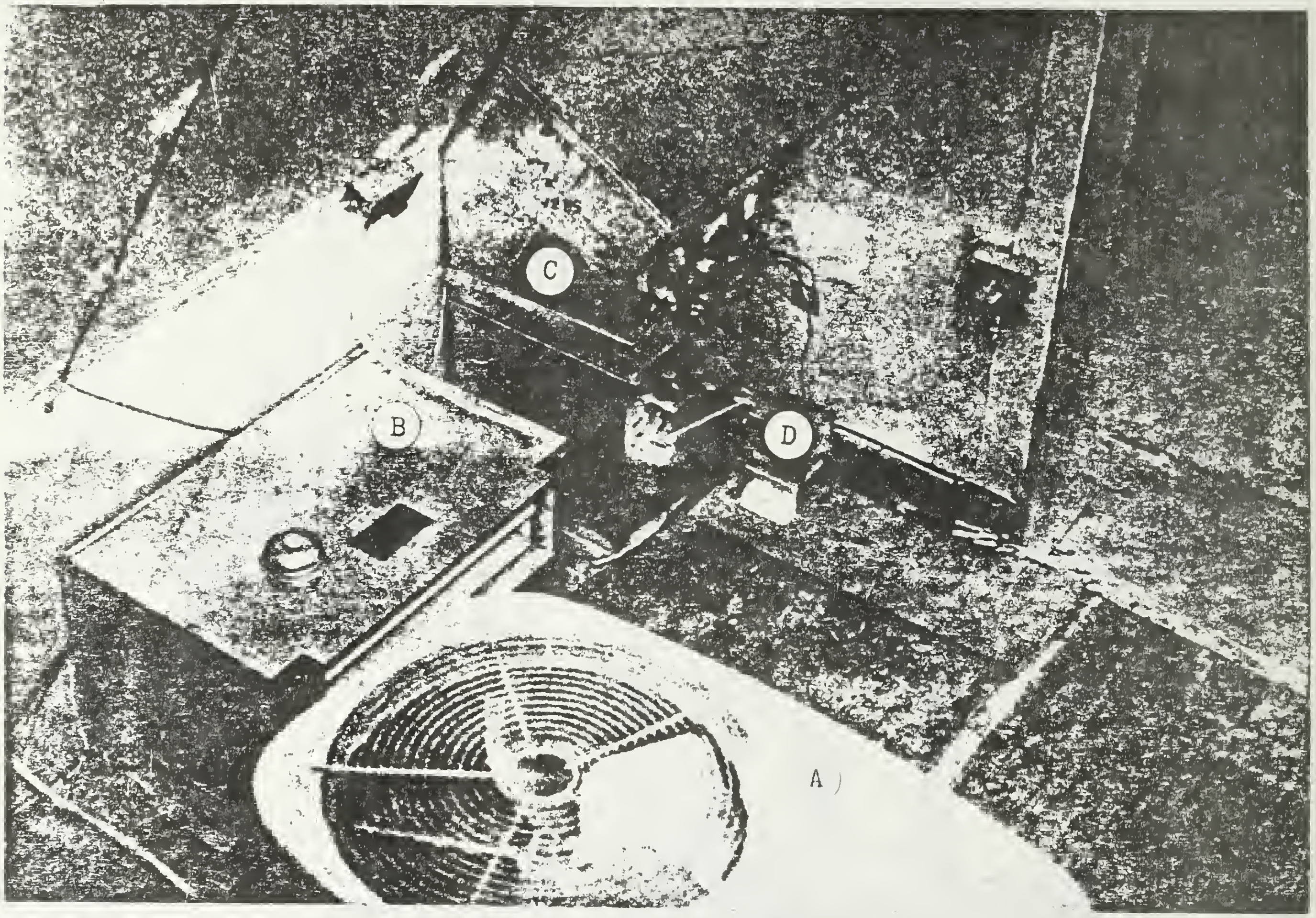
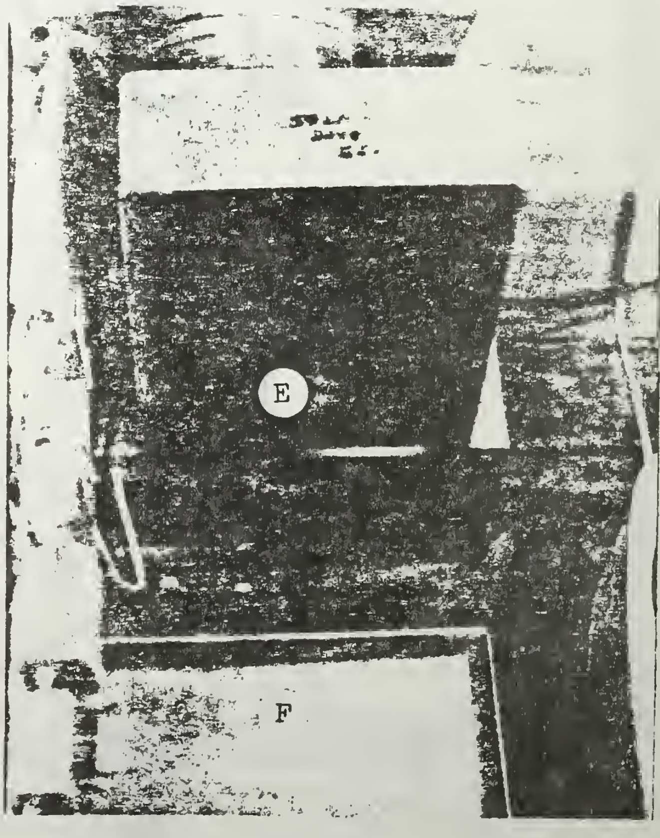


Figure 5: Schematic of Solar System Showing Transducer Layout





(A) Heat pump

(B) Rock bin outlet (fan #2)

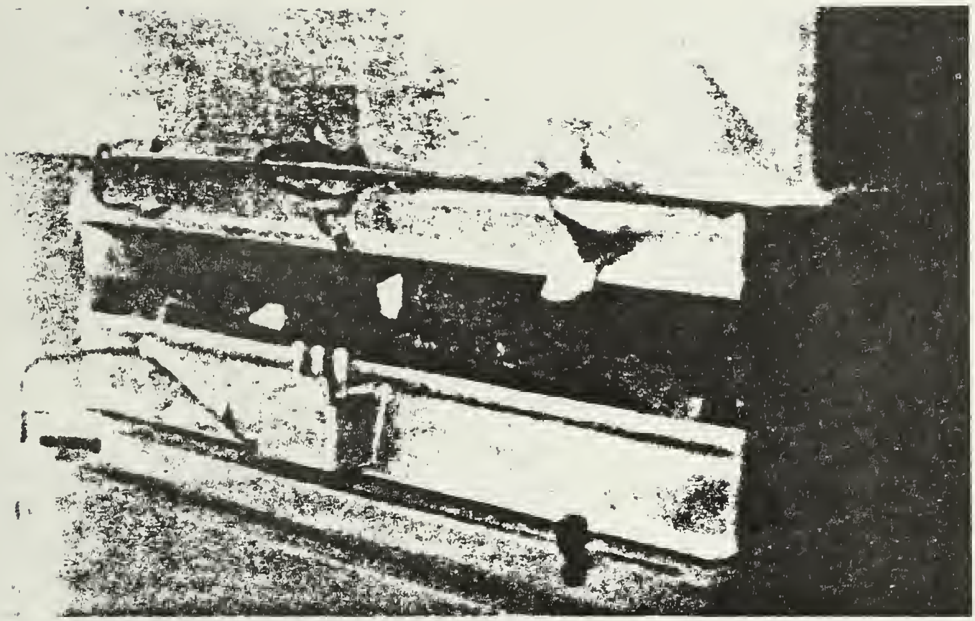
(C) Collector outlet duct temperature

(D) Motorized damper

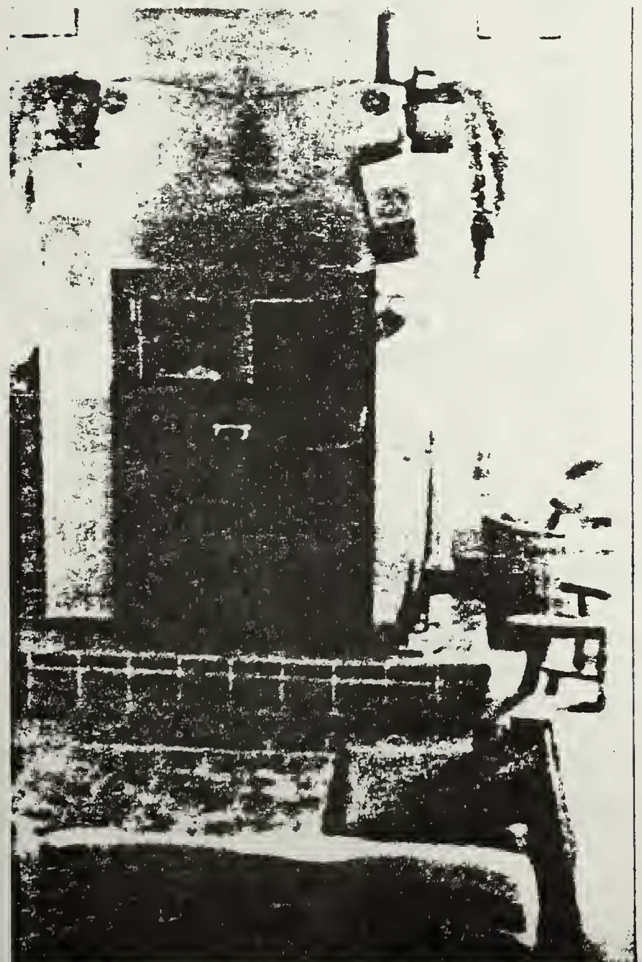
(E) Collector inlet and fan

(F) Rock bin inlet

Figure 6: Photographs of Solar System



(a) Temperature probes in auxiliary furnace inlet duct



(b) Wood burning fireplace

Figure 7: Photographs of Auxiliary Heating Systems

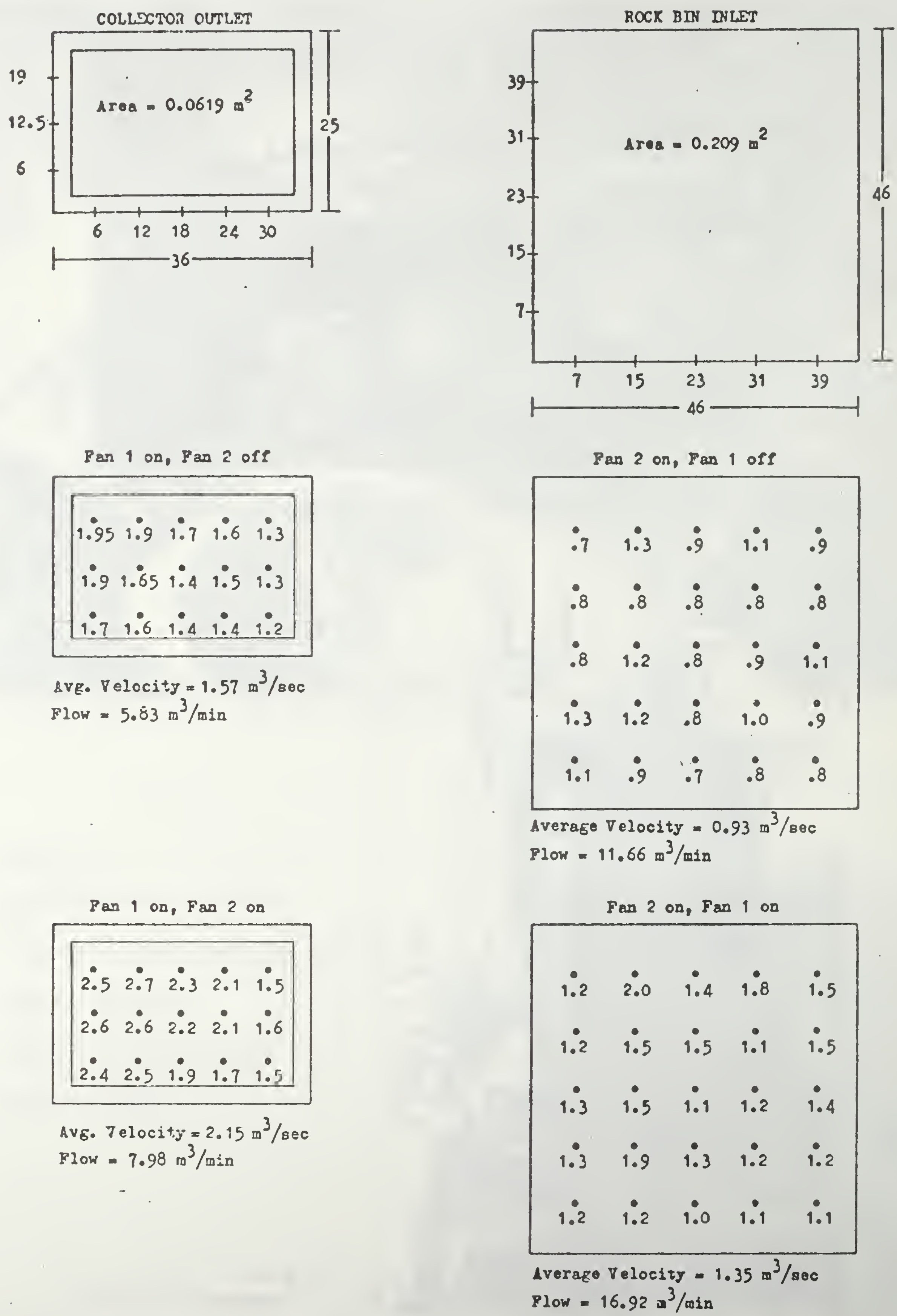
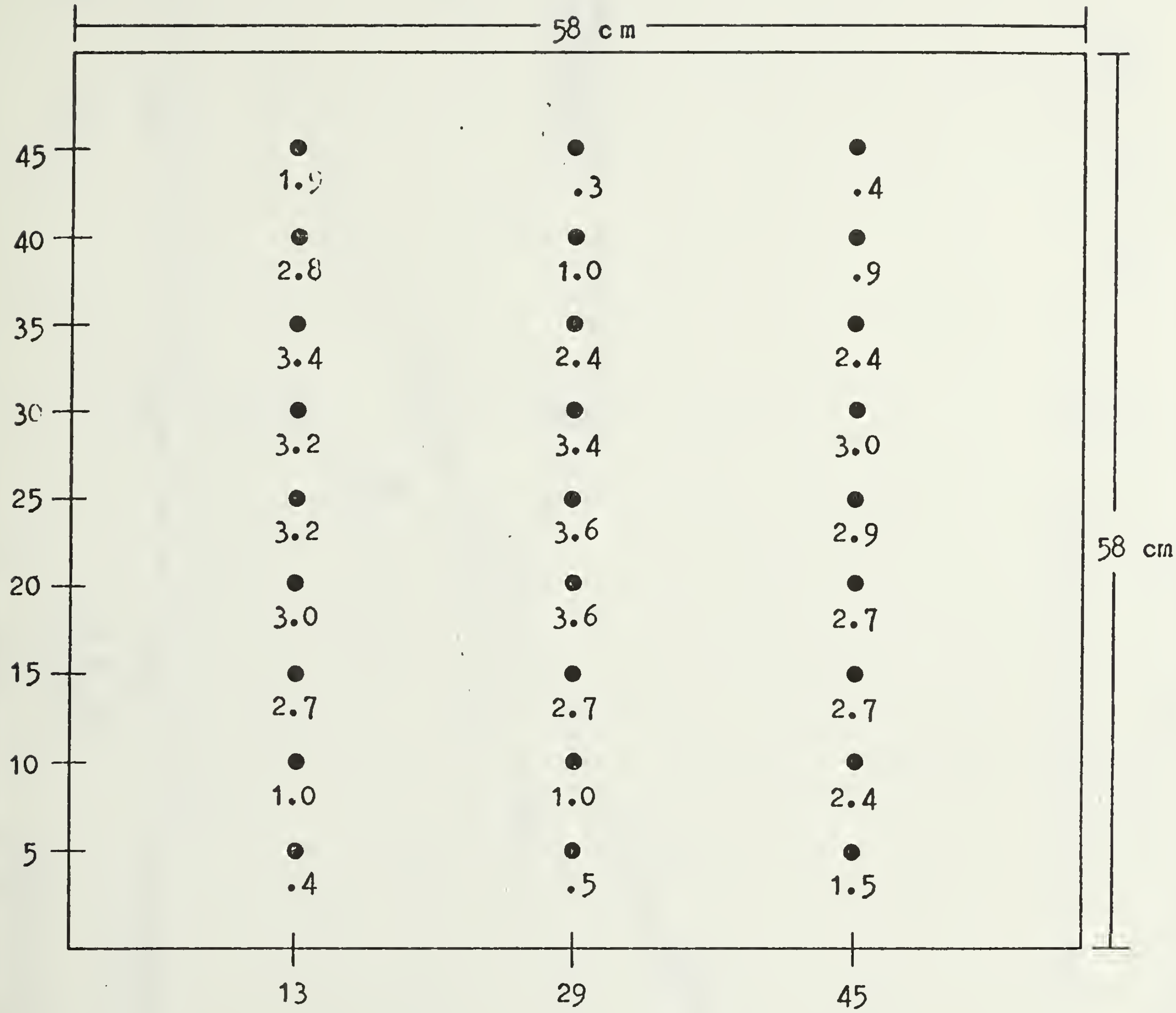


Figure 8: Air Flow in Solar Collector System



Average Velocity = 2.185 m/sec

Area = 0.297 m^2

Flow Rate = 0.648 m^3/sec = 38.91 m^3/min

Figure 9: Air Flow in Auxiliary Furnace

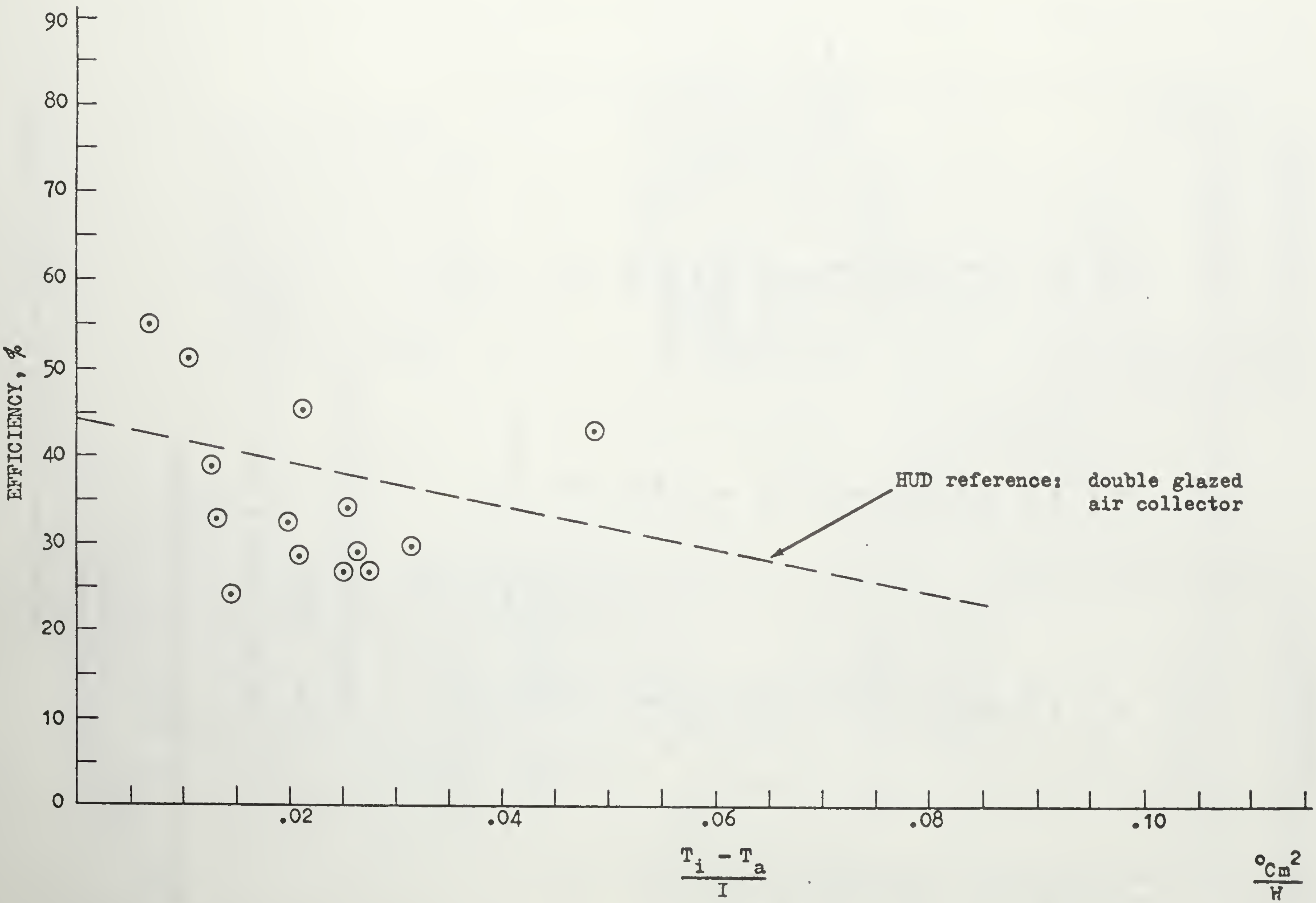


Figure 10: Collector Efficiency Curves for Leavengood System

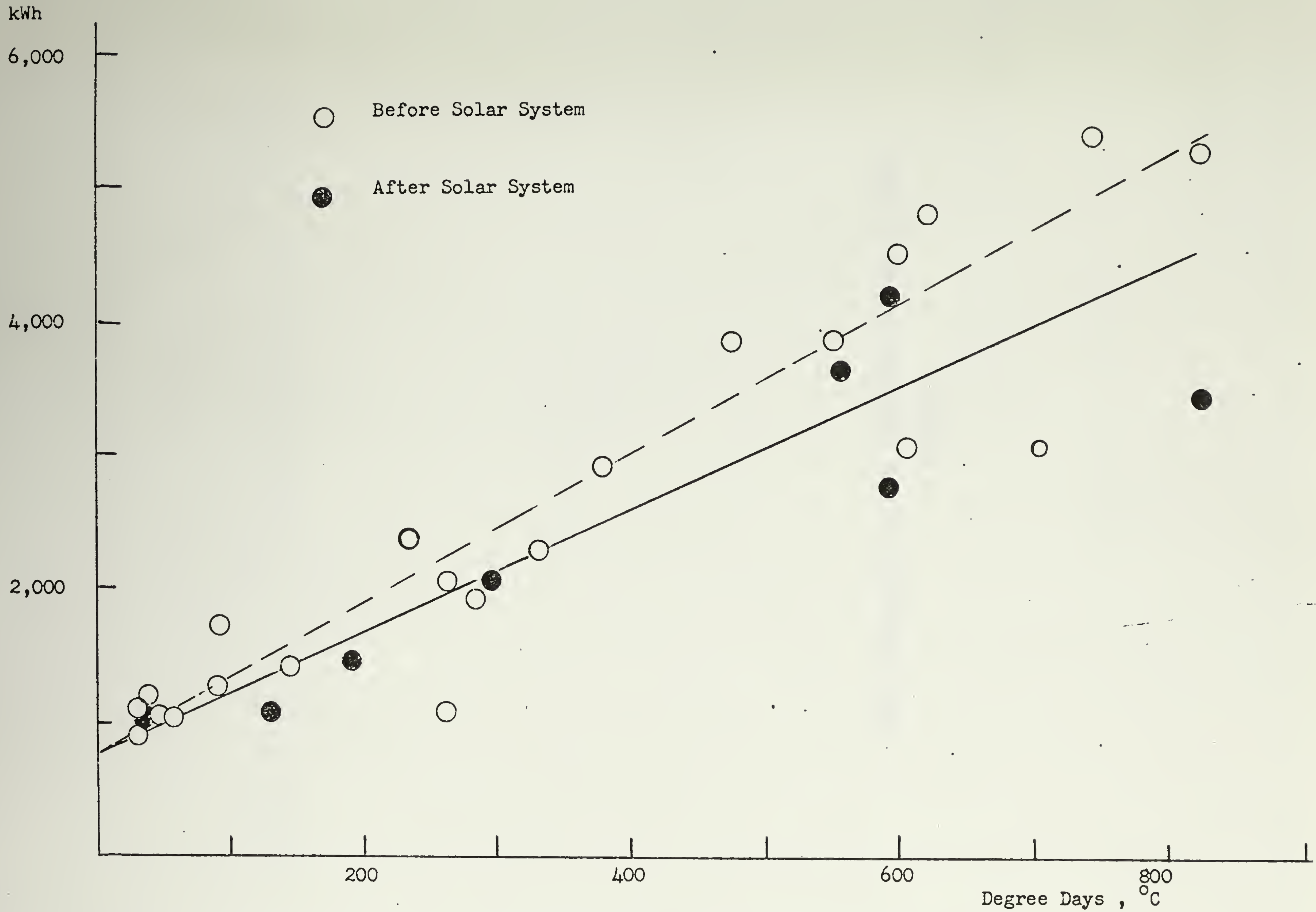


Figure 11: Utility Consumption Versus Degree-Days Showing Effect of Solar System

APPENDIX I

TABLES OF DAILY PERFORMANCE DATA FOR LEAVENGOOD HOUSE

EQUATIONS USED TO PROCESS DATA

```
500 REM *** CALCULATE HOURLY DATA ***
505 D(1)=V(1)*17.46*3.6\REM SOLAR AVAILABLE
510 D(2)=V(9)\REM COLLECTOR OUTPUT
515 D(3)=V(11)\REM ROCK STORAGE OUTPUT
520 D(4)=V(7)*.61\REM HEAT PUMP ONLY
525 D(5)=V(6)*.61\REM HEAT PUMP AND ELECTRIC
530 D(6)=V(8)*.61\REM ELECTRIC ELEMENT ONLY
535 IFABS(V(16)-V(13))<3THEN D(7)=0 ELSE D(7)=ABS(V(16)-V(13)-3)\REM FIRE PLACE
540 D(8)=V(3)*3.6\REM WATER HEATER
545 D(9)=D(4)+D(5)+D(6)+D(7)+D(8)+5.76\REM SUM OF INPUTS
546 D(11)=V(12)\REM HOUSE TEMP
547 IF D(11)<0 THEN D(11)=D(11)*2+99
550 D(10)=1.0*(D(11)-V(16))\REM ASSUMED HEAT LOAD
560 D(12)=V(16)\REM AMBIENT TEMP
565 D(13)=V(13)\REM FLUE TEMP
570 D(14)=V(14)\REM ROOM TEMP
575 D(15)=V(15)\REM ROCK BIN TEMP
580 D(16)=V(22)\REM ROCK OUTLET TEMP
585 D(17)=V(2)*3.6\REM FURNACE INPUT
590 D(18)=(4.41.045*V(14)+2.57*.115)*3.6*V(5)\REM AUXILLARY ENERGY
595 D(19)=D(5)-D(17)+D(6)+D(4)\REM HEAT PUMP
```

Note: In the data tables after the last column an "S" is printed for all hours during which the temperature of the plenum room was <u>less</u> than ambient temperature.

DAILY PERFORMANCE SUMMARY FOR THE LEAVENGOOD HOUSE 12/ 15

	SOLAR AVAIL (MJ)	COLL OUTPUT (MJ)	STORE OUTPUT (MJ)	HPUMP ONLY (MJ)	HPUMP &ELECT (MJ)	ELECT ONLY (MJ)	FIRE PLACE (MJ)	WATER HEAT (MJ)	SUN INPUT (MJ)	HOUSE LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	FLUE TEMP (C)	ROOM TEMP (C)	ROCK BIN (C)	ROCK OTLET (C)	FURN INPUT (MJ)	AUX POWER (MJ)	H.P. OUT (MJ)
1	.0	.0	.9	.0	4.0	.8	.0	.1	10.7	14.1	17.3	3.2	5.4	13.6	10.2	17.1	6.0	4.0	-1.2
2	.0	.0	.5	.0	3.0	.4	.0	.1	9.3	14.1	17.3	3.2	4.8	14.6	10.5	16.3	4.4	3.1	-1.0
3	.0	.0	.0	.0	.0	.0	.0	.1	5.8	13.5	16.4	2.9	4.6	13.6	10.5	15.4	.0	.0	-.0
4	.0	.0	.0	.0	.0	.0	.0	.1	5.8	12.5	15.7	3.2	3.9	12.6	10.6	14.7	.0	.0	-.0
5	.0	.0	.0	.0	.0	.0	.0	.1	5.8	11.5	15.2	3.7	4.6	11.9	10.5	14.1	.0	.0	-.0
6	.0	.0	.0	.0	.0	.0	.0	.1	5.8	10.6	14.8	4.2	4.8	11.3	10.2	13.6	.0	.0	-.0
7	.0	.0	.0	.0	.0	.0	.0	.1	5.8	10.1	14.4	4.3	5.0	10.9	10.1	13.2	.0	.0	-.0
8	.0	.0	.0	.0	.0	.0	.0	.1	5.8	9.9	14.1	4.2	5.1	10.7	9.9	12.9	.0	.0	-.0
9	.0	.0	.0	.0	.0	.0	.0	.1	5.8	9.7	13.8	4.1	5.1	10.4	9.8	12.6	.0	.0	-.0
10	.6	.0	1.7	.0	8.9	.4	9.9	.1	25.0	26.0	14.6	-11.4	-4.5	9.7	9.2	12.7	12.3	6.9	-3.1
11	1.9	.0	1.9	.0	10.2	1.2	.0	.1	17.2	32.3	16.2	-16.2	-14.6	8.6	8.5	11.8	14.5	9.9	-3.1
12	8.2	.0	1.3	.0	16.2	.4	.0	.1	22.4	33.7	17.2	-16.4	-14.1	9.0	8.1	10.0	21.7	15.4	-5.1
13	4.4	.0	.8	.0	6.4	.8	.0	.1	13.0	33.8	16.6	-17.1	-14.5	7.1	7.9	8.8	9.1	6.9	-2.0
14	3.1	-.8	.5	.0	6.4	1.8	.0	.1	14.0	33.5	15.7	-17.8	-15.1	7.6	7.5	7.6	10.7	8.3	-2.5
15	1.3	-.2	.5	.0	8.5	1.2	.0	.1	15.5	35.1	16.0	-19.1	-17.4	6.9	7.3	7.3	12.2	8.1	-2.5
16	.6	.0	.2	.0	20.5	.0	.0	.1	26.3	37.2	17.0	-20.3	-19.2	7.6	7.2	7.1	25.8	18.1	-5.3
17	.0	.0	-.0	.0	10.2	1.2	.0	.1	17.2	37.3	16.9	-20.4	-20.2	7.5	7.3	7.1	14.9	10.0	-3.5
18	.0	.0	.3	.0	11.1	.7	9.1	.1	26.7	37.7	16.8	-20.9	-14.8	6.6	6.8	6.8	16.0	11.1	-4.2
19	.0	.0	-.0	.0	11.8	1.1	12.5	.1	31.3	36.2	17.3	-18.9	-9.3	6.9	6.9	6.6	16.4	11.0	-3.5
20	.0	.0	-.1	.0	9.1	.8	23.2	.1	39.0	36.3	17.1	-19.2	1.0	6.8	6.8	6.4	13.3	9.2	-3.4
21	.0	.0	-.1	.0	12.2	.8	24.3	.1	43.2	36.7	17.7	-19.0	2.3	6.5	6.6	6.2	17.2	11.7	-4.1
22	.0	.0	.2	.0	5.0	.4	19.1	.1	30.2	36.6	17.0	-19.6	-3.5	5.9	6.8	6.1	7.0	4.8	-1.6
23	.0	.0	.0	.0	11.4	.8	14.8	.1	32.8	37.2	17.3	-19.9	-8.0	6.1	6.2	5.9	16.2	10.9	-4.0
0	.0	.0	-.1	.0	9.5	.8	17.8	.1	33.9	37.6	17.6	-20.0	-5.2	6.1	6.4	5.9	13.4	8.9	-3.0
	20.1	-1.0	8.4	.1	164.4	13.6	130.7	1.7	448.7	633.1	16.3	-10.1	-4.7	9.1	8.4	10.3	231.2	160.3	-53.2

COLLECTOR AUX POWER - .319194

DAILY PERFORMANCE SUMMARY FOR THE LEAVENGOOD HOUSE 12/ 16

	SOLAR AVAIL (MJ)	COLL OUTPUT (MJ)	STORE OUTPUT (MJ)	HPUMP ONLY (MJ)	HPUMP &ELECT (MJ)	ELECT ONLY (MJ)	FIRE PLACE (MJ)	WATER HEAT (MJ)	SUM INPUT (MJ)	HOUSE LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	FLUE TEMP (C)	ROOM TEMP (C)	ROCK DIN (C)	ROCK OTLET (C)	FURN INPUT (MJ)	AUX POWER (MJ)	H.P. OUT (MJ)
1	.0	.0	.2	.0	5.6	1.1	30.7	.1	43.3	36.1	17.0	-19.1	8.7	5.4	6.2	5.7	8.5	5.3	-1.7
2	.0	.0	.0	.0	.0	.0	33.2	.1	39.0	32.4	14.3	-18.1	12.1	4.8	6.7	5.5	.0	.0	-.0
3	.0	.0	.4	.0	4.6	.7	26.1	.1	37.3	31.7	13.9	-17.8	5.2	4.1	5.9	5.4	6.9	4.4	-1.5
4	.0	.0	.4	.0	5.6	.8	22.8	.1	35.1	32.7	13.9	-18.8	1.0	4.3	5.4	5.3	8.2	5.3	-1.8
5	.0	.0	.4	.0	8.9	.8	20.9	.1	36.5	33.2	14.1	-19.1	-1.1	4.5	5.1	5.2	12.5	8.1	-2.8
6	.0	.0	.1	.0	7.4	1.2	18.1	.1	32.6	33.8	14.2	-19.6	-4.5	5.3	5.6	5.3	10.6	6.7	-2.0
7	.0	.0	.3	.0	5.5	.8	16.9	.1	29.0	31.8	13.9	-17.9	-4.0	4.4	5.2	5.0	7.9	5.1	-1.6
8	.0	.0	.4	.0	8.3	1.1	14.6	.1	29.9	31.2	14.0	-17.2	-5.6	4.3	5.0	4.9	12.0	7.7	-2.4
9	1.3	.0	-.2	.0	14.4	.4	15.1	.1	35.8	31.3	15.4	-15.9	-3.7	5.2	5.1	4.8	19.9	13.8	-5.1
10	3.8	.0	-.6	.0	17.5	.4	11.7	.1	35.4	30.8	18.0	-12.9	-4.1	5.5	5.5	4.6	23.9	16.7	-6.1
11	6.9	.0	-.4	.0	12.5	.7	9.9	.1	28.9	27.9	18.0	-9.9	-3.0	5.3	5.7	4.5	17.7	12.4	-4.5
12	13.2	.0	-.1	.0	4.4	.7	16.8	.1	27.7	25.2	17.2	-8.0	5.8	5.3	5.9	4.5	6.7	4.4	-1.6
13	40.2	5.9	2.6	.0	8.8	.4	15.2	.1	30.2	22.2	17.5	-4.7	7.4	7.3	6.1	8.9	12.2	8.7	-3.0
14	37.1	11.2	1.8	.0	6.6	.3	15.4	.1	28.2	21.9	18.7	-3.2	9.2	12.0	6.8	13.4	9.3	6.8	-2.4
15	37.7	12.9	.0	.0	.0	.0	17.6	.1	23.4	16.4	17.4	1.0	15.6	11.0	6.6	10.4	.1	.0	-.1
16	5.0	8.5	.0	.0	.0	.0	24.7	.1	30.5	19.2	16.7	-2.5	19.2	11.1	6.8	10.1	.0	.0	-.0
17	.6	.8	.0	.0	.0	.0	19.3	.1	25.1	19.3	15.8	-3.5	12.8	9.8	7.2	9.9	.0	.0	-.0
18	.0	.0	.0	.0	.0	.0	17.0	.1	22.8	19.0	15.0	-4.0	10.0	9.3	7.4	11.9	.0	.0	-.0
19	.0	.0	1.6	-.0	8.4	.4	13.2	.1	27.7	19.3	15.7	-3.6	6.6	10.2	8.2	13.8	11.7	8.3	-3.0
20	.0	.0	1.2	.0	5.6	.7	11.5	.1	23.6	18.5	17.0	-1.6	6.9	11.4	9.3	15.1	8.2	5.8	-1.9
21	.0	.0	.4	.0	1.8	.3	9.4	.1	17.4	18.1	16.7	-1.4	5.0	10.9	9.4	14.7	2.9	2.1	-.7
22	.0	.0	.0	.0	.0	.0	10.8	.1	16.6	16.9	15.4	-1.5	6.3	9.9	9.4	14.0	.0	.0	-.0
23	.0	.0	.0	.0	.0	.0	8.9	.1	14.7	14.5	14.7	.2	6.1	9.1	9.2	13.6	.0	.0	-.0
0	.0	.0	.0	.0	.0	.0	8.7	.1	14.5	14.2	14.2	-.0	5.7	8.7	9.0	13.2	.0	.0	-.0
	145.8	39.4	8.3	.1	125.8	11.0	408.5	1.7	685.3	597.5	15.8	-9.1	4.9	7.5	6.8	8.7	179.3	121.8	-42.5

COLLECTOR AUX POWER - 4.1383322

DAILY PERFORMANCE SUMMARY FOR THE LEAVENGOOD HOUSE 12/ 17

	SOLAR AVAIL (MJ)	COLL OUTPUT (MJ)	STORE OUTPUT (MJ)	LPUMP ONLY (MJ)	HPUMP SELECT (MJ)	ELECT ONLY (MJ)	FIRE PLACE (MJ)	WATER HEAT (MJ)	SUN INPUT (MJ)	HOUSE LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	FLUE TEMP (C)	ROOM TEMP (C)	ROCK BIN (C)	ROCK OTLET (C)	FURN INPUT (MJ)	AUX POWER (MJ)	H.P. OUT (MJ)	
1	.0	.0	.0	.0	.0	.0	7.9	.1	13.7	13.7	13.7	.0	4.9	8.3	8.8	12.9	.0	.0	-.0	
2	.0	.0	.4	.0	1.8	.4	8.2	.1	16.1	12.7	13.4	.7	5.8	8.2	8.6	12.7	2.8	1.8	-.7	
3	.0	.0	.4	.0	1.8	.4	6.9	.1	14.9	13.5	13.6	.1	4.0	8.7	8.6	12.8	2.8	1.8	-.6	
4	.0	.0	.4	.0	1.9	.4	7.0	.1	15.1	14.2	13.5	-.7	3.3	8.9	8.7	12.6	2.8	1.8	-.5	
5	.0	.0	.7	.0	5.0	.8	.0	.1	11.6	13.8	13.8	.0	2.6	9.6	8.8	12.4	7.5	5.0	-1.7	
6	.0	.0	.2	.0	1.9	.4	.0	.1	8.1	11.9	13.5	1.7	3.3	9.8	9.1	12.0	2.9	1.8	-.6	
7	.0	.0	.7	.0	7.0	.4	.0	.1	13.2	9.8	14.0	4.1	5.3	9.6	8.9	11.6	9.5	6.8	-2.2	
8	.0	.0	.1	.0	16.8	.4	.0	.1	23.1	12.8	17.6	4.8	5.9	10.4	9.4	10.3	21.7	15.4	-4.5	
9	.6	.0	-.3	.0	8.9	1.2	.0	.1	15.9	12.5	18.0	5.5	6.6	9.8	9.7	9.3	12.9	8.7	-2.8	
10	2.5	.0	-.1	.0	4.8	.8	.0	.1	11.4	12.3	17.8	5.5	7.0	9.3	9.4	8.8	7.1	5.0	-1.6	
11	5.7	.0	-.0	.0	2.0	.4	.0	.1	8.2	9.5	17.3	7.7	9.1	9.6	9.5	8.6	3.1	2.0	-.7	
12	7.5	.0	.0	.0	.0	.0	.0	.1	5.8	7.1	16.5	9.4	10.1	9.9	9.8	8.6	.0	.0	-.0	
13	4.4	.0	.0	.0	.0	.0	.0	.1	5.8	6.4	16.1	9.7	10.9	9.9	9.8	8.4	.0	.0	-.0	
14	3.1	.0	.0	.0	.0	.0	.0	.1	5.8	6.2	15.7	9.5	10.7	9.8	9.8	8.2	.0	.0	-.0	
15	4.4	.0	.0	.0	.0	.0	.0	.1	5.8	5.7	15.5	9.8	11.7	9.9	9.8	8.1	.0	.0	-.0	
16	3.1	.0	-.1	.0	3.2	.4	.0	.1	9.4	6.1	15.7	9.6	10.6	9.9	9.6	8.1	4.6	3.1	-1.0	
17	.6	.0	-.3	.0	6.8	.9	.0	.1	13.5	9.3	17.1	7.8	9.0	9.4	9.2	8.3	9.6	6.6	-1.9	
18	.0	.0	-.3	.0	4.6	4.3	.0	.1	14.8	10.8	18.4	7.6	8.3	11.0	9.4	8.5	11.4	4.5	-2.5	
19	.0	.0	.0	.0	.0	2.0	.0	.1	7.8	11.3	17.6	6.3	7.4	10.8	9.7	8.8	2.6	.0	-.5	
20	.0	.0	.0	.0	.0	.0	.0	.1	5.8	11.5	16.6	5.1	6.3	10.8	9.7	8.5	.0	.0	-.0	
21	.0	.0	.0	.0	.0	.0	.0	.1	5.8	8.1	16.1	8.1	7.8	10.5	9.7	8.3	.0	.0	-.0	
22	.0	.0	.0	.0	.0	.0	.0	.1	5.8	6.3	15.7	9.5	8.8	10.2	9.6	8.2	.0	.0	-.0	
23	.0	.0	.0	.0	.0	.0	.0	.1	5.8	5.3	15.4	10.1	9.4	9.9	9.6	8.1	.0	.0	-.0	S
0	.0	.0	.0	.0	.0	1.9	.0	.1	7.7	5.7	15.6	9.9	9.2	9.6	9.5	8.0	2.5	.0	-.6	S
	32.1	.0	1.8	.1	65.4	15.0	27.9	1.7	251.4	236.7	15.8	5.9	7.4	9.7	9.4	9.7	104.1	64.5	-22.6	

COLLECTOR AUX POWER - 0

APPENDIX II

DATA ACQUISITION SYSTEM

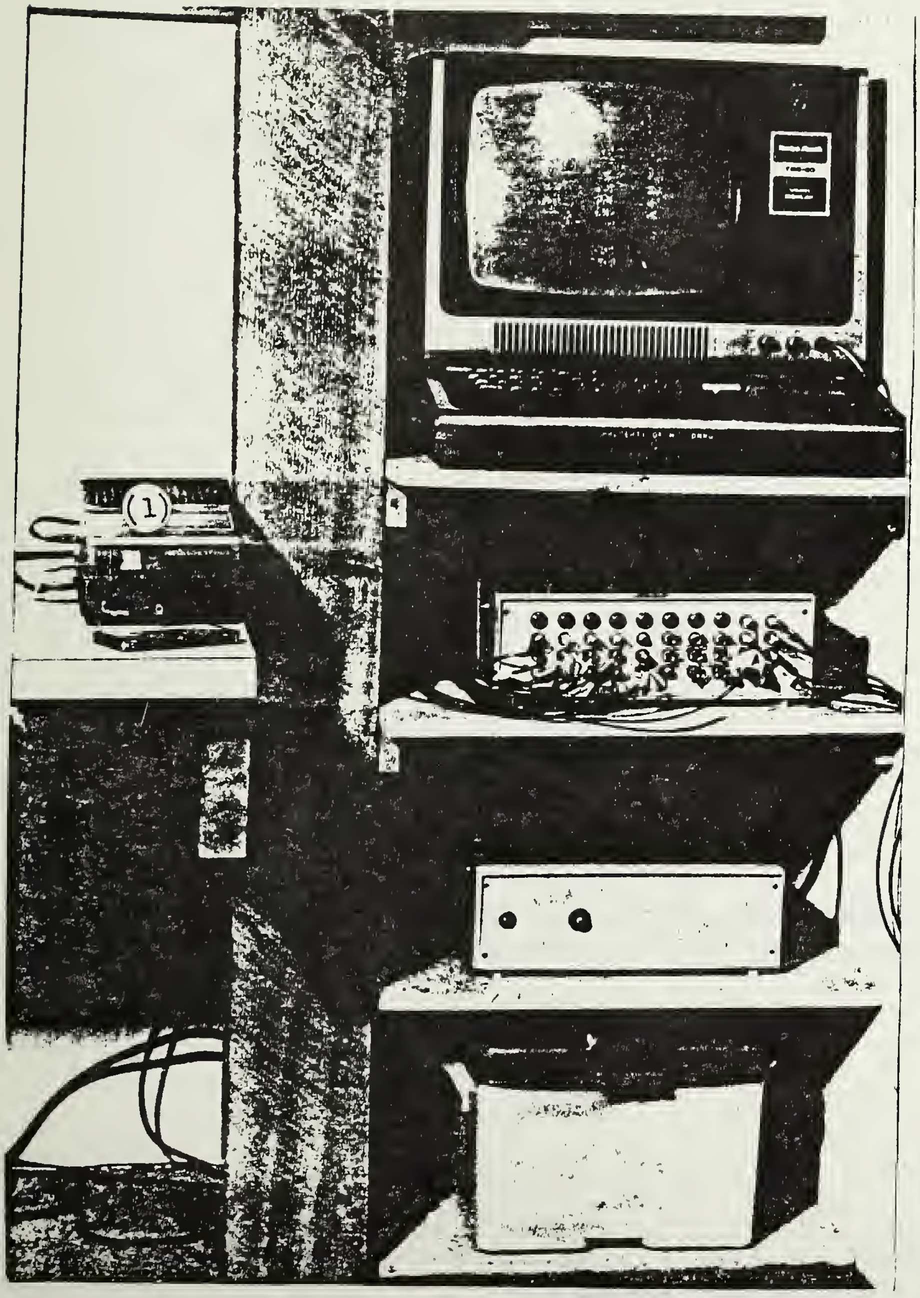
A low cost data acquisition system was developed for solar performance monitoring and is pictured in Figure 1 on the following page. The heart of the system is a Radio Shack TRS-80 computer having a 4K memory. This system has the capability of 40 input channels and is controlled by a Level II BASIC program which allows the user to structure data sampling and processing procedures. Calibration constants, error checks, scan rate, data averaging, printing, etc., can be manipulated using this program capability. A real time clock within the A/D converter chassis is used to time the data output on the cassette. Scanning at an average rate of 40 channels per five seconds, the data is averaged at the end of each hour. This data is then written onto the cassette recorder for processing at a later time.

Temperatures were measured using AD-590 transducers made by Analog Devices. A BASIC computer program was used with the data acquisition system to calibrate the probes against a precision thermometer. The absolute accuracy of the temperatures measured is better than 0.5°C (1°F), while the accuracy of small temperature differences is 0.1°C (0.18°F).

Total solar radiation on the collector surface was measured using a silicon cell pyranometer. The device was manufactured by the contractor and is mounted in the plane of the solar collector. The device has been referenced to NOAA Standards with an estimated overall accuracy of 5%.

Electric power is measured using clamp-on ammeters calibrated on-site against the utility kWh meter. The status of motors, dampers, curtains and fans is determined using appropriate relays, microswitches or mercury switches.

Flow in liquid systems is measured using Hersey MVR-30 turbine meters which have been interfaced to the DAS. Flow in air systems is mapped using a hot-wire anemometer for a one-time measurement to characterize the flow. Status switches and software combine the one-time measurements to calculate appropriate heat flow quantities.



— Video display of current data scan: 40 channels, time, date

— Keyboard for controlling system

(1) Cassette for storing data and programs

— 40 channels analog input, A/D conversion (12 bit), real time clock

— Power supply for computer and A/D interface

— 12V battery: powers system up to 5 hours in the event of a power shortage

Figure 1: Computer-Based Data Acquisition System

THERMAL PERFORMANCE

OF THE TRAVER/H.R.D.C. MOBILE HOME RETROFIT SOLAR SYSTEM

by

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for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM

Grant #RAE-145-800

NOTE ON UNITS

The test results in this report are given in metric or SI units. This convention corresponds to current professional practice and is in accord with the recommendations of the International Solar Energy Society and most technical journals.

Most readers are familiar with the Celsius or Centigrade temperature scale (^{o}C) and with power measured in kilowatts (kW). The metric unit of energy is the Joule (J). Most energy quantities in this report are expressed in megajoules (MJ) which is 10^6 joules or a million joules (1,000 BTU = 1 kBTU = 1.05 MJ). Since one MJ is about one thousand BTU's, a furnace with a rating of 100 thousand BTU/hour would be rated at about 100 MJ/hour. This approximate conversion will be useful to the reader accustomed to thinking in thousands of BTU.

Other abbreviations included in this report are: l = liters, m = meters, m^2 = square meters and kWh = kilowatt hours.

ABSTRACT

This project is a mobile home located a few miles south of Missoula, Montana, belonging to Lynda and John Traver. This home was retrofit with active air solar collectors built by the Missoula Human Resources Development Council. The area of the collectors is 10.8 m^2 (100 ft^2). They are mounted against the south wall of the trailer. Air is drawn from the trailer through the collectors and returned directly to the trailer. No heat storage was used.

During the test period of 56 days during the spring of 1980, the solar collectors produced an insignificant amount of heat. This poor performance was due to: (a) air leaks in the ducting system and (b) control malfunctions.

The data indicated that the existing windows in the trailer were contributing a passive solar gain equal to 12% of the total heat requirements of the home. During the test period, the auxiliary propane furnace supplied 42% of the heat and internal electric gains supplied 46%.

SOLAR COLLECTOR

Type: Active air
Manufacturer: Site-built by HRDC
Aperture Area: 10.8 m^2
Glazing: Flat stock filon
Absorber: 0.024" aluminum painted flat black
Fluid: Air
Thermal Capacity: 0.0015 MJl^{-1} $^oC^{-1}$
Flow Rate: 2.52 m^3 min^{-1}
Tilt: 90°
Azimuth: 180°

AUXILIARY HEAT

Type: Forced air
Manufacturer: Coleman
Fuel: Propane
Capacity: 19 $MJhr^{-1}$

BUILDING

Type: Trailer house
Floor Area: 84.4 m^2
Calc. Loss Factor: 0.67 $MJhr^{-1}$ $^oC^{-1}$
Measured Loss Factor: 0.61 $MJhr^{-1}$ $^oC^{-1}$

TABLE OF CONTENTS

TABLES

FIGURES

1.0 INTRODUCTION

The Traver residence is located several miles south of Missoula, Montana. Active air solar collectors were site-built and attached to this mobile home by the Missoula Human Resources Development Council. A large number of systems similar to this have been installed in the Missoula area. The Traver project was judged to be the most efficient and best constructed of these projects by the designer, Ken Boggs.

2.0 DESCRIPTION OF THE HOUSE AND SOLAR SYSTEM

The Traver residence is a manufactured home with overall dimensions of 4.2 x 20 m (14 x 66 ft) and is oriented with the 20 m (66 ft) dimension along the east-west axis. Metal skirting is used and two entry-ways approximately 2.4 m (8 ft) square have been added to each of the exterior doors. This home is moderately well insulated and has been maintained in good condition. Figures 1 and 2 show photographs of the Traver residence. A floor plan drawing of the residence is shown in Figure 3 and the calculated heat load for this home is shown in Table 1.

The solar system consists of two banks of air collector panels mounted vertically on the south wall of the trailer, Figure 1(a). The solar collector fan is located in the crawl space beneath the trailer and is actuated by a thermostat switch in the collector panel. When the thermostat temperature reaches its set point, the fan is turned on and air is drawn from the living space of the trailer through the collector, through the fan, and the solar heated air is returned to the living space of the trailer. Figure 4(a) shows photographs of the solar collector control. Figure 4(b) shows a portion of the insulated flexible ducting and the fan box located beneath the trailer.

Figure 5 shows a schematic of the solar system. There are three separate inlet ducts leading to the collector. These ducts are located in the living room, the kitchen and the bedroom. There are two outlet ducts from the collector, one located in the hall and one in the kitchen. The location of these ducts is shown in the floor plan in Figure 3.

3.0 TRANSDUCER ARRANGEMENT AND FLOW MEASUREMENTS

The data acquisition system used on this project is described in Appendix II. The arrangement of the transducers is shown in the schematic in Figure 5. A transducer log is given in Figure 6 which describes the locations of the individual probes. There were two probes inside the trailer to measure the air temperature of the living space. One probe was located in the living room on the west end of the mobile home, near the wood stove. The second probe was located in the master bedroom on the east end. An ambient air temperature probe was placed on the north wall of the trailer inside a radiation shield. The air temperature in the crawl space was also monitored near the center of the home.

Solar radiation was measured in the plane of the solar collectors by a silicon cell transducer attached to the collectors. The air temperature at the collector inlets was measured by a set of three temperature probes connected so as to measure the average inlet temperature. A single probe was placed in each of the collector outlet ducts in the kitchen and the hallway. A status relay was connected to the collector circulating fan to indicate to the data acquisition system when the fan was on.

The auxiliary gas furnace was instrumented with a set of three averaging probes in the inlet and a second set of three averaging probes in the outlet duct. A status relay was connected to the motor which powers the furnace fan. Air flows in the furnace are shown in Figure 7. Clamp-on ammeters were installed in the main electric entry panel to measure total electric power entering the mobile home.

All air flows were measured using a hot-wire anemometer. Figure 8 shows the air velocities measured at several points on the cross-sections of the collector inlet and outlet ducts. Of the three collector inlet ducts, only the living room duct (which is closest to the collectors) showed a significant flow. The total inlet flow of the three inlet ducts is 2.52 m^3 per minute. The flow in the two outlet ducts also was unbalanced, with the kitchen collector outlet having about three times the flow of the hall collector outlet. The total outlet flow was 6.1 m^3 per minute.

Comparison of the inlet and outlet collector flows shows that there was a large leak in the collector ducting system amounting to 3.58 m^3 per minute, or nearly half of the total outlet flow. This leakage flow was due to (a) leaks in the collector panels outside the trailer, (b) leaks in the ducting system and/or (c) leaks in the fan box in the crawl space beneath the trailer. This leakage can be expected to seriously degrade the thermal performance of the solar collector system.

It should be noted that Ken Boggs rebuilt the ducting system before this monitoring project was begun. This work was required because the ducts had been mashed and pulled off, apparently by some dogs who were living in the crawl space. The performance before the monitoring was probably even poorer.

The solar collectors have a very good exposure to the sun. A shading diagram is shown in Figure 9. This diagram indicates the only shading is due to the mountain range lying to the east of the project. This shading is insignificant. Table 2 shows a comparison of insolation measured at the site during April and May to the insolation measured in downtown Missoula at Hellgate High School. The Missoula data is measured on a 60° tilted surface as part of the Solar Insolation Measurement Montana Program that is sponsored by DNR&C.

This 60° data was converted using an approximate algorithm to predict the radiation that would have been measured at the Missoula site on a 90° or vertical surface. Table 2 shows that the monthly totals agree to within better than 20%. These differences can be attributed to differences in microclimate, shading, reflection and instrument calibration. It can be concluded that the Missoula data was sufficiently accurate to use for solar design purposes on this project.

4.0 DATA ANALYSIS AND RESULTS

The data analysis relies on an hourly heat balance performed on the trailer. In this heat balance, the sum of the hourly energy inputs to the trailer are equated to the hourly heat load. Energy inputs include solar heat entering the trailer, furnace heat entering the trailer and electrical dissipation from lights, appliances, etc., in the trailer.

The heat load is calculated from an overall heat loss factor multiplied by the difference in temperature between the inside air temperature and the ambient air temperature.

In the initial stages of the data reduction and error checking process, the solar input was assumed to come exclusively from the solar collectors. This analysis showed that the solar collectors were producing negligible amounts of heat. This was due to (a) control malfunctions which failed to turn on the collector fan even though solar energy was available and (b) low collector outlet temperatures, probably due to dilution of the solar heated air with leakage air drawn from the cool crawl space or ambient air, Figure 7.

The hourly heat balances showed that during any sunny day there was a deficit on the input side of the heat balance equation. This suggested that solar heat was somehow entering the trailer. Inspection of the floor plan of the house showed that there were a large number of south facing windows in the trailer having a total area equal to about 2/3 of the collector area itself. This observation suggested that we introduce a passive solar gain component into the input side of the heat balance equation. This passive component was based on the solar radiation in the plane of the window, the total window area, and an estimated transmission coefficient of the windows.

The introduction of this passive input into the heat balance equation caused a remarkable improvement in the hourly, daily and monthly heat balances. The passive solar input was, therefore, included as a permanent part of this analysis.

There was a wood stove in the trailer which was not used during the monitoring period in order to increase the accuracy of the monitoring data. The Missoula HRDC volunteered to pay the additional auxiliary fuel costs to the owner. A temperature probe located near the stove showed that, indeed, the owners cooperated with this plan and did not use the stove.

A sample of the hourly heat balance summary for one day is shown in Table 3. Hourly data for the entire monitoring period are shown in Appendix I. In Table 3, the first column, COLLECTOR INPUT, shows the total solar radiation falling on the surface of the collectors in

megajoules (MJ). The second column, COLLECTOR OUTPUT, shows the heat delivered by the collectors to the living space. The last four columns in Table 3 relate to collector operation. These columns show collector inlet and outlet temperatures (^{o}C), collector efficiency and the last column shows the total hours of operation of the collector fan. During this sunny day, the collector fan operated a total of 0.5 hour. The collector operated for 0.22 hour between 12:00 and 1:00 p.m. During this time, the collector outlet temperature was only 7^{o} C above the house temperature. The data for this day is typical and illustrates both the control and leakage problems that characterized this solar system.

The next three columns in the Table show the PASSIVE SOLAR energy entering the building, the FURNACE OUTPUT entering the building, and the ELECTRICAL dissipation in the building. All inputs are added together and listed in the next column, SUMM INPUT. A comparison of the SUMM INPUT and HEAT LOAD columns, both on an hourly and daily total basis, allows an evaluation of the accuracy of the data.

For this particular day, during the early morning hours, heat was being supplied entirely by the furnace and with small amounts of electrical dissipation. The heat balance in the early morning shows close agreement, which verifies the accuracy of the measurement of furnace input energy. The agreement of the heat balance is less precise during the middle of the day when the sun is shining on the building. This lack of agreement is primarily due to thermal storage effects and transient effects, which are not considered in this steady state heat balance. Note that while the house temperature is very stable during the early morning hours, it increases during the day and then decreases late in the day.

On this day the crawl space temperature is often below ambient temperature and always below house temperature, and ambient temperature is always below house temperature. It is clear that air leaks in the collector system would have the effect of diluting the temperature output of the collectors. During colder weather, this leakage would cause relatively greater reductions in efficiency.

The bottom line of each daily summary gives totals of the energy

quantities and averages of the temperature quantities for that day. Table 4 summarizes these daily averages and total performance quantities for the entire monitoring period. Scanning the COLLECTOR OUTPUT column in these Summary Tables shows that on some occasions the collector output was negative. A negative collector output occurs when the collector circulation fan is running at a time when the inlet temperature is higher than the outlet temperature. These negative outputs mean that the solar collector system is cooling rather than heating the trailer.

Table 5 shows an overall summary for the Traver project. This Table shows the total and average data for each month as well as the overall total and average data. During the monitoring period, the solar collector system contributed 0.2% to the overall heat requirements of the house. This is a negligible amount of heat and barely exceeds the electrical power used to drive the solar collector circulating fan. The collectors averaged an efficiency of 0.4% during the monitoring period. The overall efficiency of a collector of this type during this time of year should be 25-35%. This poor performance is related to the design, construction and operational problems discussed previously.

Passive solar gain through the windows supplied 12% of the heat requirements of the house, the auxiliary furnace 42% and electrical dissipation 46%. In Table 4, the total HEAT INPUT and CALCULATED HEAT LOAD columns agree quite closely, which verifies the energy balances presented. The house temperature during the monitoring period was a comfortable 21.7° C, while the ambient temperature was 8.05° C. Table 6 shows the monthly utility records of electric power of the Traver house, beginning in January of 1978 and extending through the monitoring period. Table 7 shows corresponding degree-day data.

5.0 COMPUTER PREDICTION

A performance prediction of this system was made using an f-chart design analysis. The solar radiation data input into the design analysis was from measurements made in Missoula as part of the Solar

Insolation Measurement Montana (SIMM) Program. Weather data for degree-days and ambient temperatures are taken from long-term averages for Missoula. The collector performance data input into this design routine assumes a typical double-glazed air collector with an area of 10.8 m^2 in good operating condition, Table 8.

The f-chart design procedure predicts an annual solar fraction of 15% for this system. During the monitoring period, the f-chart procedure predicts a solar fraction greater than 20%. This exceeds the measured solar fraction by a factor of 100. During April and May, the solar radiation measured at the site in the plane of the collector was 2.6 $kWh\text{-}m^{-2}$.

The overall heat load for April and May averaged 178MJ per day. This was computed using the measured heat load factor of $0.61 MJhr^{-1}\ {}^{o}C^{-1}$. The average measured house temperature during this period was 22° C and the ambient temperature was 9.65° C.

For the same period of two months, the f-chart predicts an average heat load of $103 MJ\text{-}day^{-1}$, based on a calculated heat loss factor of $0.67 MJhr^{-1}\ {}^{o}C^{-1}$. The f-chart calculation assumes a house temperature of 18.3° C and an average ambient temperature of 9.55° C. If the heat loads for the monitoring data and the f-chart analysis are adjusted to the same house temperature, ambient temperature and heat loss factor base, the results agree to within better than 2%.

It can be concluded that the environmental data during the monitoring period was typical of long-range average environmental data. It is, therefore, reasonable to predict that this solar system should have produced around 2,000MJ during the monitoring period, or about 100 times the measured energy output of about 25MJ.

TABLE 1

TRAVER TRAILER HEAT LOAD

	R	U (Btu/hr ft^2 ^oF)	Area (sq. ft.)	U X A
Ceiling	20	0.05	908	45
Floor	12	0.083	908	76
Walls	12	0.083	1178	98
Windows	1.72	0.58	117	68
*Infiltration:	7260 ft^3 X ½ X .018			65
				352 Btu/hr ^oF
			or	0.67 MJ/hr ^oC

*Assuming ½ air change/hour

NOTE: Average measured value = 0.61MJhr^{-1} $^oC^{-1}$

TABLE 2

INSOLATION COMPARISON, kWh-m^{-2}-day^{-1}

MONTH	MEASURED MISSOULA DATA @ 60°	CALCULATED MISSOULA DATA @ 90°	MEASURED TRAVER SITE DATA @ 90°
April	3.85	2.66	2.87
May	3.80	2.31	2.09

TABLE 3

SAMPLE HOURLY PERFORMANCE FOR ONE DAY

PERFORMANCE SUMMARY FOR THE TRAVER PROJECT 4/ 19/80

HR	COLL INPUT (MJ)	COLL OUTPUT (MJ)	PASSV SOLAR (MJ)	FURN OUTPUT (MJ)	ELECT INPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	CRAWL SPACE (C)	COLL INLET (C)	COLL OUTLET (C)	COLL EFF	SFAN STAT (HRS)
1	.00	.00	.00	5.50	2.95	8.45	8.66	21.52	7.32	10.15	8.11	9.67	.00	.00
2	.00	.00	.00	5.96	1.94	7.90	8.60	21.39	7.28	9.72	7.46	9.23	.00	.00
3	.00	.00	.00	6.73	3.02	9.75	8.83	21.34	6.87	9.59	7.37	9.02	.00	.00
4	.00	.00	.00	7.59	2.23	9.82	9.38	21.30	5.92	9.20	6.51	8.63	.00	.00
5	.00	.00	.00	6.83	2.23	9.06	9.93	21.30	5.02	9.05	5.82	8.42	.00	.00
6	.00	.00	.00	7.89	2.99	10.88	10.68	21.18	3.68	8.86	4.70	8.29	.00	.00
7	.75	.00	.17	7.58	2.45	10.20	9.88	21.27	5.08	9.03	6.22	8.33	.00	.00
8	2.34	.00	.52	4.01	4.14	8.67	8.62	21.56	7.42	9.51	9.72	8.42	.00	.00
9	5.05	.00	1.13	.00	3.17	4.30	7.99	22.12	9.01	10.07	14.61	8.77	.00	.00
10	10.25	.00	2.26	.00	2.99	5.25	6.21	22.88	12.69	11.46	18.99	9.85	.00	.00
11	14.11	.00	3.13	.00	1.69	4.82	4.85	21.72	13.76	12.41	18.62	11.71	.00	.00
12	17.47	-.09	3.92	.00	2.09	5.91	4.50	22.32	14.94	13.03	22.74	18.84	.00	.11
13	22.62	.64	5.05	.00	.76	6.44	3.79	23.99	17.78	13.99	23.69	30.09	.03	.22
14	23.75	.51	5.31	.00	4.86	10.68	2.05	23.92	20.56	15.63	22.23	28.05	.02	.14
15	16.58	.06	3.74	.00	5.15	8.95	.91	24.05	22.55	16.59	21.03	21.78	.00	.03
16	9.56	.00	2.09	.00	5.72	7.81	.45	24.26	23.51	16.36	19.87	19.79	.00	.00
17	8.94	.00	2.00	.00	3.89	5.89	.39	24.70	24.05	16.54	21.86	20.69	.00	.00
18	4.67	.00	1.04	.00	5.00	6.05	.81	24.95	23.61	16.17	23.68	21.72	.00	.00
19	1.74	.00	.35	.00	5.04	5.39	.93	23.30	21.77	15.60	22.21	20.45	.00	.00
20	.21	.00	.00	.00	4.14	4.14	3.68	23.48	17.44	14.79	18.77	17.22	.00	.00
21	.00	.00	.00	.00	3.92	3.92	4.41	23.27	16.03	14.33	15.11	15.02	.00	.00
22	.00	.00	.00	.00	3.71	3.71	5.71	23.55	14.19	13.45	12.85	12.80	.00	.00
23	.00	.00	.00	.00	6.80	6.80	7.24	23.19	11.32	12.39	10.85	11.79	.00	.00
0	.00	.00	.00	.00	.68	.68	7.51	21.71	9.39	11.63	9.83	11.10	.00	.00
*	138.04	1.12	30.71	52.09	81.58	165.50	136.03	22.67	13.38	12.48	14.71	14.57	.00	.50

*Daily Total Energy, Daily Average Temperatures

TABLE 4

DAILY SUMMARY

MARCH

DAILY PERFORMANCE SUMMARY FOR THE TRAVER PROJECT 3/ 26/80

DA	COLL INPUT (MJ)	COLL OUTPUT (MJ)	PASSV SOLAR (MJ)	FURN OUTPUT (MJ)	ELECT INPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	CRAWL SPACE (C)	COLL INLET (C)	COLL OUTLET (C)	SFAN STAT (HRS)
26	.15	.00	.00	39.24	24.30	63.54	64.76	20.96	3.26	5.45	4.69	5.30	.00
27	58.60	.00	12.88	152.30	103.25	268.42	170.77	14.83	3.17	6.28	1.79	5.46	.00
28	96.64	-.22	21.66	121.28	90.65	233.37	260.95	21.18	3.36	5.80	8.24	6.14	.18
29	73.09	-.37	16.27	153.97	73.76	243.63	220.03	20.23	4.55	6.31	8.36	6.45	.13
30	54.79	.00	12.18	166.53	113.36	292.07	302.75	20.06	-.62	2.51	8.42	3.08	.00
31	78.54	.00	17.40	195.30	81.25	293.95	299.74	19.97	-1.39	2.34	10.53	2.74	.00

APRIL

DAILY PERFORMANCE SUMMARY FOR THE TRAVER PROJECT 4/ 1/80

DA	COLL INPUT (MJ)	COLL OUTPUT (MJ)	PASSV SOLAR (MJ)	FURN OUTPUT (MJ)	ELECT INPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	CRAWL SPACE (C)	COLL INLET (C)	COLL OUTLET (C)	SFAN STAT (HRS)
1	42.35	.00	9.48	198.05	110.12	317.66	321.59	20.42	-.67	2.65	3.72	2.97	.00
2	107.46	.16	23.84	160.42	103.14	287.56	271.38	19.89	1.35	4.04	6.63	5.78	.35
3	185.82	3.77	41.50	137.38	96.77	279.42	265.77	21.44	3.29	5.83	13.01	10.76	1.31
4	24.80	.24	5.48	17.17	76.21	99.10	104.47	22.58	5.45	9.02	9.69	8.60	.11
5	94.57	-.41	21.05	89.30	112.00	221.94	231.32	21.83	6.02	7.20	9.69	7.46	.20
6	60.63	.19	13.49	139.12	110.95	263.75	262.64	20.77	2.83	5.96	5.69	6.32	.21
7	115.24	-.37	25.67	185.54	102.28	313.11	271.31	20.08	1.55	5.05	12.33	5.51	.25
8	73.71	-.07	16.36	152.26	82.12	250.66	248.81	19.43	2.48	5.14	11.82	4.52	.01
9	38.50	.00	8.44	130.92	112.50	251.86	240.65	20.23	3.79	6.94	17.28	5.79	.00
10	68.77	-.25	15.23	152.74	114.91	282.62	270.83	21.18	2.68	5.87	21.26	5.44	.04
11	164.92	.42	36.80	95.60	79.09	211.92	251.93	22.05	4.84	6.97	21.27	10.73	1.00
12	150.62	2.03	33.58	85.79	61.78	183.17	218.98	20.89	5.28	7.54	16.50	10.87	.96
13	171.50	3.87	38.19	89.16	79.20	210.42	220.33	23.81	8.76	9.24	11.92	12.33	.98
14	146.21	3.50	32.63	41.13	103.25	180.50	173.28	23.07	11.24	11.02	14.38	13.03	.87
15	74.76	-.11	16.70	72.08	62.96	151.64	202.47	20.76	6.93	8.84	10.72	8.44	.03
16	170.18	4.26	37.93	74.32	59.08	175.53	203.93	21.79	7.87	9.38	13.59	12.39	1.09
17	153.73	1.30	34.10	57.51	60.70	153.61	151.25	22.90	12.57	11.53	15.25	13.05	.56
18	163.68	.79	36.54	23.53	55.37	116.23	135.59	22.99	13.73	12.75	16.35	13.66	.42
19	138.04	1.12	30.71	52.09	81.58	165.50	136.03	22.67	13.38	12.48	14.71	14.57	.50
20	142.90	.77	31.93	24.21	110.45	167.36	93.86	21.66	14.91	14.36	15.12	14.24	.34
21	149.01	.71	33.15	22.84	52.38	109.08	121.32	22.39	14.11	13.87	16.24	14.99	.51
22	100.99	1.07	22.53	29.78	85.61	138.99	125.12	21.87	13.32	13.10	15.28	14.35	.57
23	142.65	.86	31.93	46.00	81.18	159.97	141.43	22.90	13.24	13.75	15.79	14.53	.45
24	23.94	.00	5.31	41.13	69.26	115.70	161.32	21.36	10.34	11.81	11.79	11.36	.00
25	82.89	-.06	18.27	44.39	55.22	117.82	153.79	22.02	11.52	11.96	13.57	11.93	.15
26	151.80	-.07	33.76	46.03	92.52	172.24	139.75	22.76	13.21	13.17	16.19	15.17	.23
27	148.21	.13	32.80	42.42	69.37	144.72	110.49	22.30	14.75	13.50	15.57	14.14	.27
28	134.37	.04	29.93	40.53	130.54	201.03	91.92	22.33	16.05	15.23	17.45	14.93	.21
29	34.94	.00	7.57	38.20	47.12	92.89	109.94	21.47	11.46	12.80	13.61	12.18	.00

TABLE 4

DAILY SUMMARY, CONTINUED

MAY

DAILY PERFORMANCE SUMMARY FOR THE TRAVER PROJECT 5/ 3/80

DA	COLL INPUT (MJ)	COLL OUTPUT (MJ)	PASSV SOLAR (MJ)	FURN OUTPUT (MJ)	ELECT INPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	CRAWL SPACE (C)	COLL INLET (C)	COLL OUTLET (C)	SFAN STAT (HRS)
3	49.36	.00	10.96	15.16	32.69	58.81	13.13	19.07	16.91	15.20	15.53	15.19	.00
4	141.25	-.18	31.41	38.00	68.54	137.77	94.29	21.54	15.10	14.18	15.33	14.52	.17
5	140.36	-.01	31.32	50.47	66.10	147.88	76.74	22.07	16.83	14.48	17.18	14.76	.23
6	84.39	-.04	18.79	3.87	88.96	111.58	124.01	22.65	14.17	14.79	15.95	13.73	.12
7	32.08	.00	6.96	26.61	61.99	95.56	139.41	19.85	10.33	11.47	12.40	11.19	.00
8	124.36	.04	27.67	31.36	87.55	146.62	145.01	22.18	12.28	12.81	15.11	13.40	.30
9	28.11	.00	6.26	78.81	87.77	172.84	183.86	20.87	8.31	10.57	11.54	10.45	.00
10	29.38	.00	6.44	74.68	98.35	179.47	176.35	19.60	7.55	9.19	9.96	9.32	.00
11	128.17	-.46	28.54	90.73	96.26	215.07	194.04	22.53	9.27	10.61	12.88	11.37	.32
12	134.95	.64	29.93	68.39	86.90	185.86	165.94	21.56	10.22	11.56	13.25	13.84	.73
13	94.08	-.15	20.88	47.92	76.10	144.75	174.13	21.79	9.90	11.57	13.21	12.12	.34
14	131.66	1.16	29.32	45.86	110.74	187.08	169.62	22.15	10.57	12.79	14.39	14.39	.77
15	96.26	.00	21.40	45.66	55.30	122.36	165.82	22.16	10.83	11.85	13.15	11.16	.00
16	73.16	-.21	16.18	90.14	67.90	174.01	204.61	21.26	7.28	9.36	11.44	9.78	.15
17	121.02	.01	27.06	20.50	44.53	92.10	141.42	21.73	12.07	12.30	14.93	13.45	.53
18	111.75	-.14	24.88	36.05	76.75	137.54	103.97	21.84	14.40	13.39	15.39	13.29	.10
19	69.70	.00	15.49	6.37	77.29	99.15	97.89	24.17	17.48	14.91	18.26	14.04	.00
20	116.10	.00	25.75	16.62	60.08	102.46	103.89	25.33	18.24	16.12	19.79	14.64	.00
21	103.92	.00	22.97	14.90	142.92	180.79	105.47	26.41	19.21	17.60	19.91	17.19	.00
22	73.35	.00	16.10	3.98	76.07	96.14	121.54	22.76	14.45	15.01	16.49	14.67	.00
23	19.24	.00	4.09	166.99	74.05	245.13	249.53	20.04	2.99	7.91	8.21	8.22	.00
24	59.09	.00	13.31	109.72	74.27	197.30	219.03	22.11	7.15	9.29	10.85	9.29	.00
25	10.78	.00	2.35	156.03	101.99	260.37	248.37	21.80	4.83	8.53	7.35	8.48	.00
26	75.49	.00	16.79	95.66	70.88	183.34	221.07	21.48	6.38	8.42	10.94	8.40	.00
27	.00	.00	.00	6.80	4.86	11.66	17.20	19.42	5.32	8.60	6.73	8.75	.00

TABLE 5

OVERALL SUMMARY FOR TRAVER PROJECT

Month	Days	Solar Available	Solar Collector Output	Fan Power	Passive Solar Gain	Auxiliary Furnace	Elec Input	Total Input	*Heat Load	House Temp	Ambient Temp
		MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ	°C	°C
March	4	303	0.59	0.4	67	637	359	1063	1083	20.36	1.48
April	29	3257	23.69	4.9	723	2330	2458	5534	5437	21.72	8.49
May	23	1999	.65	3.8	430	1319	1851	3600	3631	22.08	10.82
TOTAL	56	5559	24.93	9.1	1220	4286	4668	10197	10151	**21.70	**8.05
DISTRIBUTION			0.20%		12%	42%	46%	100%			

*Calculated

**Average

TABLE 6

MONTHLY UTILITY RECORDS OF ELECTRIC POWER

	1978 kWh	1979 kWh	1980 kWh
January	734	807	836
February	744	769	1031
March	746	539	714
April	652	481	909
May	574	475	849
June	470	541	653
July	429	502	648
August	358	460	
September	530	486	
October	534	493	
November	820	668	
December	749	794	

TABLE 7

MISSOULA DEGREE DAY DATA

(Degrees Celsius)

Month	Long-Term Average	1978 Degree Days	1978 Ratio	1979 Degree Days	1979 Ratio
January	785	699	.89	1022	1.30
February	611	583	.95	610	.99
March	521	428	.82	496	.95
April	338	313	.93	347	1.03
May	202	283	1.40	216	1.07
June	97	95	.98	70	.72
July	12	37	3.08	20	1.66
August	31	61	1.97	7	.22
September	162	171	1.05	67	.41
October	346	335	.97	287	.82
November	551	633	1.15	627	1.14
December	712	841	1.18	579	.81
TOTAL	4368	4479	1.02	4348	.99

TABLE 8

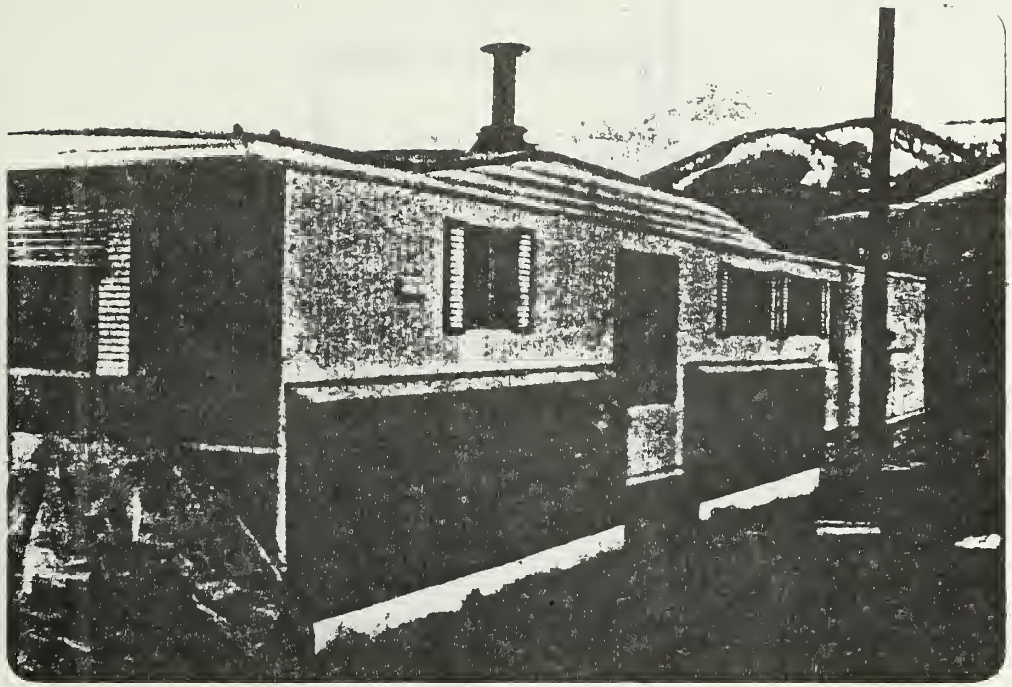
PREDICTED PERFORMANCE USING F-CHART

MON	----DAILY---- SOLAR RAD KWh/m2	AMBT TEMP (C)	----MONTHLY---- DEGREE DAYS (C-DAY)	WATER LOAD KWh	HEAT LOAD KWh	TOTAL LOAD KWh	SOLAR FRAC (%)	SOLAR ENERGY KWh	BACKUP ENERGY KWh
JAN	2.2	-7.0	786	0	3507	3507	5	184	3323
FEB	2.1	-3.5	611	0	2728	2728	6	159	2569
MAR	2.8	1.5	522	0	2329	2329	14	323	2006
APR	2.9	7.1	338	0	1510	1510	23	349	1161
MAY	2.2	12.0	203	0	905	905	25	230	675
JUN	2.6	15.7	98	0	436	436	70	306	130
JUL	2.8	20.2	12	0	55	55	100	54	1
AUG	3.3	18.9	32	0	141	141	100	141	0
SEP	3.4	13.2	162	0	724	724	64	461	263
OCT	3.7	7.2	346	0	1545	1545	34	520	1025
NOV	2.2	-.1	552	0	2463	2463	7	182	2281
DEC	1.4	-4.7	713	0	3182	3182	1	27	3155
YEAR	2.6	6.7	4375	0	19525	19525	15	2936	16589

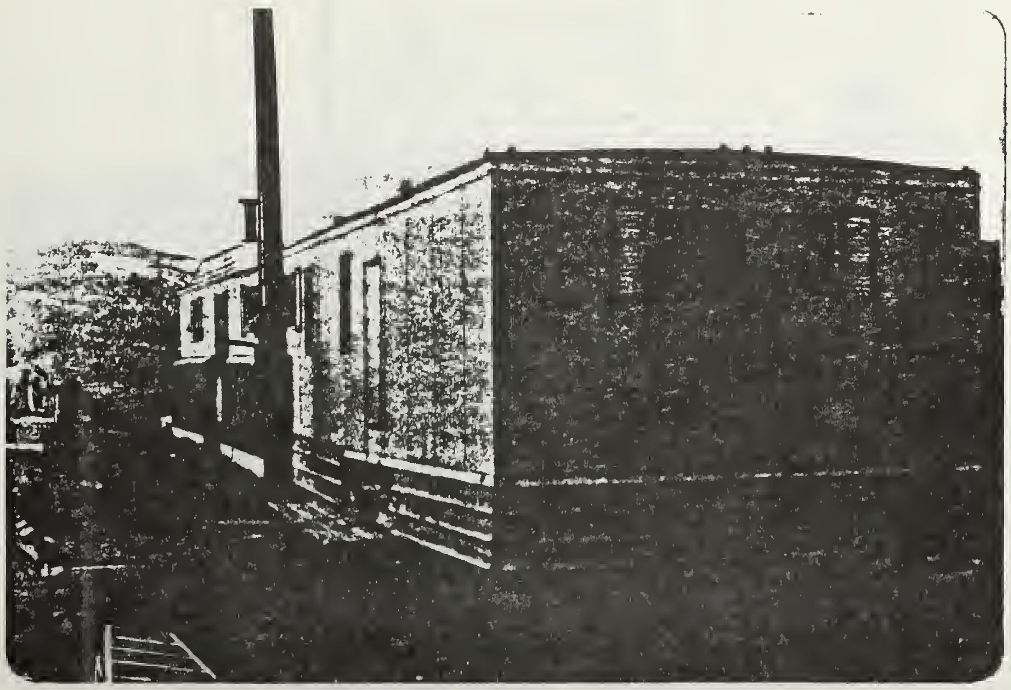
YEARLY SOLAR FRACTION.... .15

CLIENT.................... TRAVER
LOCATION.................. MISSOULA

COLLECTOR AREA........... 10.80 m2, 116.2 ft2
COLLECTOR TILT........... 90 DEGREES
COLLECTOR TYPE........... AIR
EFFICIENCY SLOPE......... 5.00 W/C-m2, .88 BTU/F-ft2
Y-INTERCEPT.............. .60
HOUSE LOAD FACTOR........ .19 KWh/C-HOUR, 332 BTU/F-HOUR



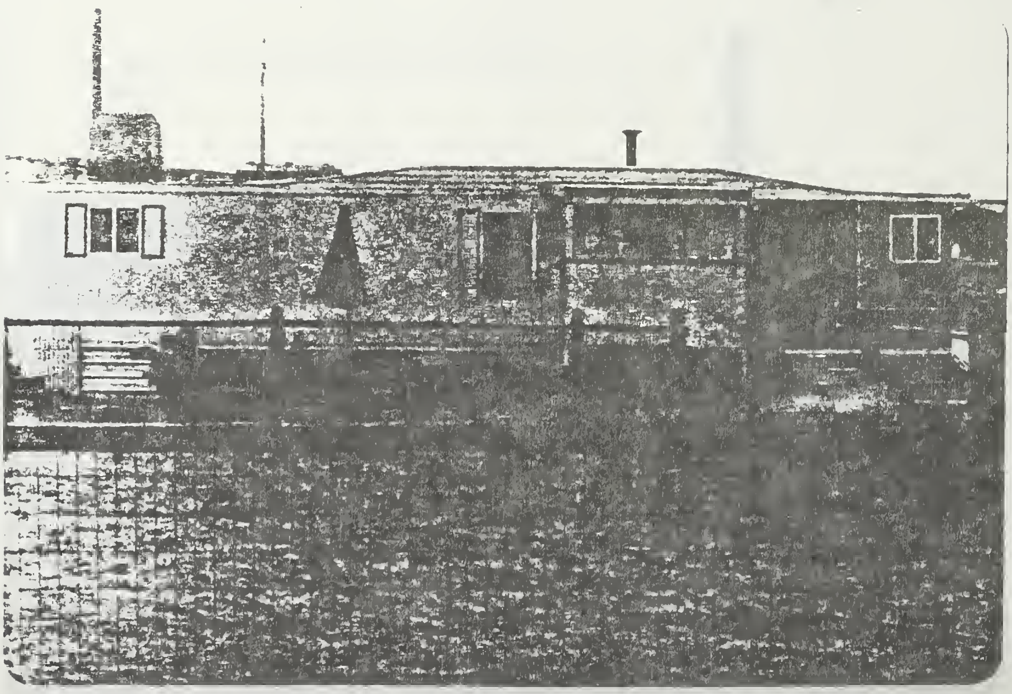
(a) Solar collector panels on south wall



(b) Solar panels

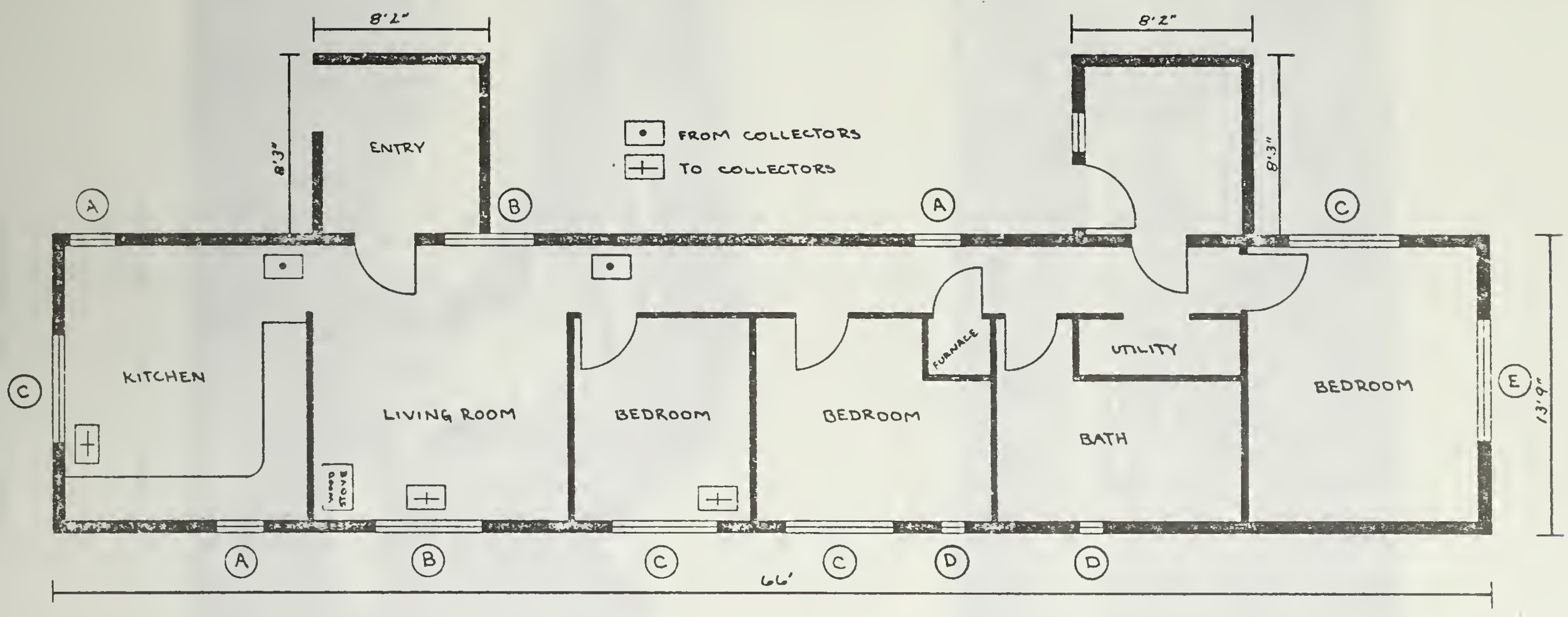
Figure 1: Traver Mobile Home

(a) Northeast corner



(b) North wall and main entry

Figure 2: Traver Mobile Home



WINDOW SCHEDULE

	SIZE	# WINDOWS	SQ FT.
A	2825	3	14.6
B	6050	2	41.6
C	6025	4	41.6
D	1440	2	7.7
E	6825	1	11.8
TOTALS		12	117.3

Figure 3: Floor Plan of Traver Residence

(a) Collector controls

(b) Insulated, flexible ducting

Figure 4: Solar Hardware

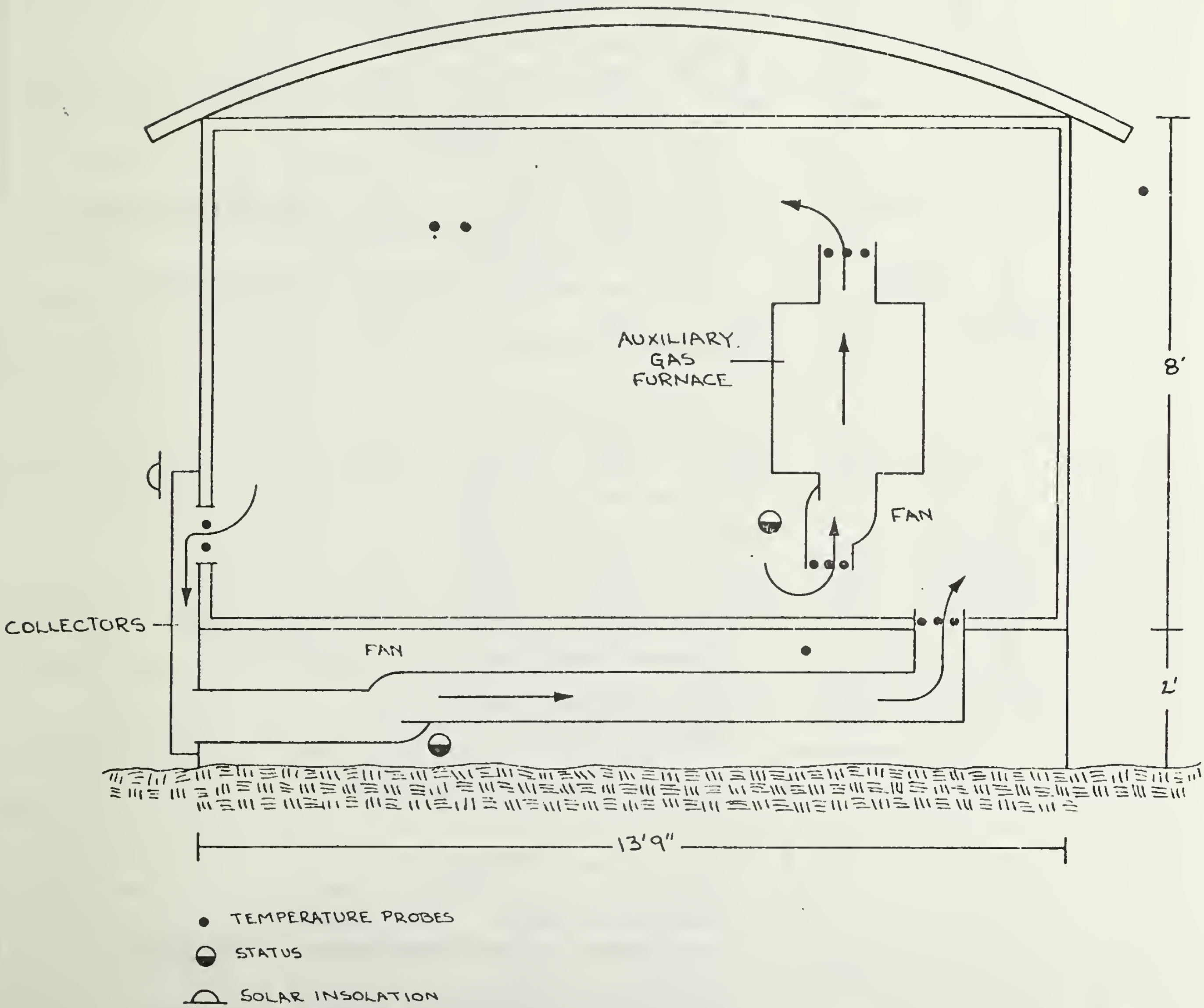


Figure 5: Schematic of Traver Solar System Showing Principle of Operation and Transducer Arrangement

FIGURE 6
TRANSDUCER LOG

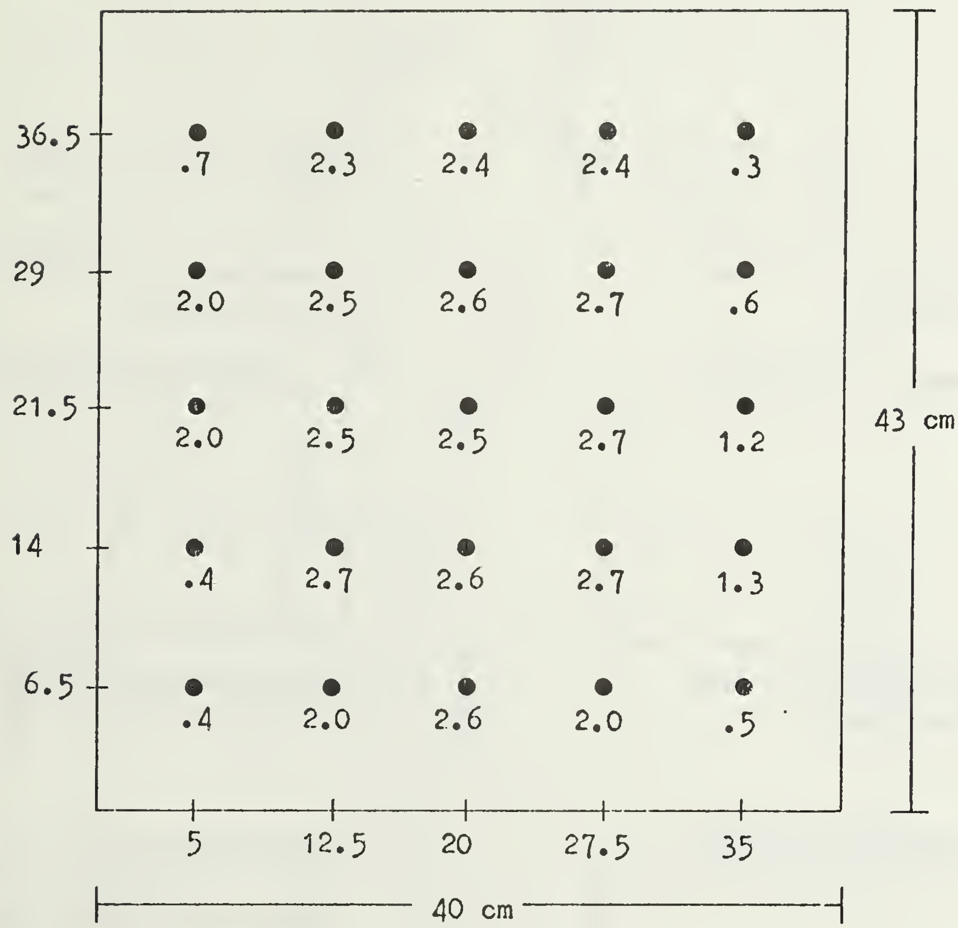
TYPES:

S - SOLAR
T - TEMP
DT - DUCT TEMP
ST - STATUS
P - POWER

TRAVER TRAILER

DISK #	RS #	PROBE #	TYPE	LOCATION AND MOUNTING
1	1	1	S	Solar Transducer mounted on face of Collector surface
2	2		P	Amp Clamp on one phase of 110V in Main Breaker Box
3	3		P	Amp Clamp on one phase of 110V in Main Breaker Box
4	5	Relay	ST	Solar Fan Status: Relay connected in parallel with Collector Fan
5	8	Relay	ST	Furnace Fan Status: Relay connected in parallel with Furnace Fan
6	9		C	Collector Input
7	10		C	Collector Output
8	11		C	Collector Efficiency
9	17		C	Furnace Heat Output
10	25	36	T	Crawl Space Temperature: Located under Freezer Room 20cm beneath the floor
11	26	20	T	Freezer Room Temperature: Located 20cm from ceiling
12	27	11	T	Master Bedroom Temperature
13	28	6	T	Living Room Temperature
14	29	31	DT	Collector Outlet: Single probe in outlet duct of the West Bank of Collectors
15	30	8	DT	Collector outlet: Single probe in outlet duct of the East Bank of Collectors
16	31		(T)	Averaged Collector Outlets
17	32	21	T	Ambient Temperature: Located on north side of Trailer 1.5cm above the ground in a radiation shield
18	33	60 68, 71	DT	Collector Inlet: Averaging set in the three inlet ducts to Collectors
19	37	59 61, 62	DT	Furnace Inlet: Averaging set located behind vented door of Furnace Room
20	38	10 67, 72	DT	Furnace Outlet: Averaging set in the outlet duct of the Furnace

FURNACE INLET



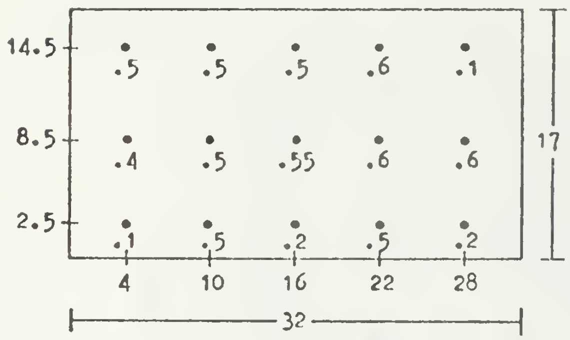
Area = .175m^2

Average Velocity = 1.86m/sec.

Volume Flow Rate = 19.58m^3/min.

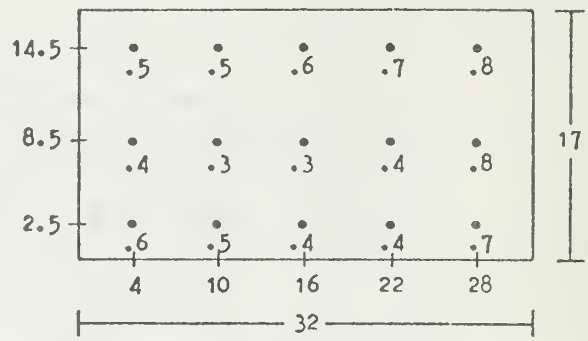
Figure 7: Flow Measurements in Furnace System

LIVING ROOM COLLECTOR INLET



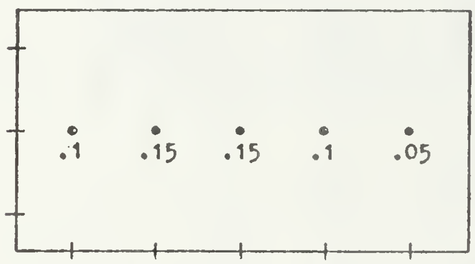
Average Velocity = .41 m/sec
Flow = 1.29 m^3/min

HALL COLLECTOR OUTLET



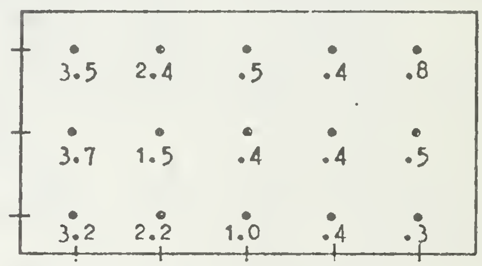
Average Velocity = .53 m/sec
Flow = 1.67 m^3/min

KITCHEN COLLECTOR INLET



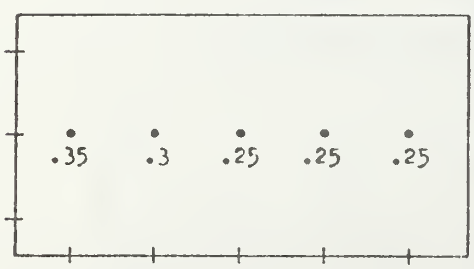
Average Velocity = .11 m/sec
Flow = .346 m^3/min

KITCHEN COLLECTOR OUTLET



Average Velocity = 1.41 m/sec
Flow = 4.43 m^3/min

BEDROOM COLLECTOR INLET



Average Velocity = .28 m/sec
Flow = .88 m^3/min

Total Outlet Flow = 6.1 m^3/min

Total Inlet Flow = 2.52 m^3/min

Leakage Flow = 6.1 − 2.52 = 3.58 m^3/min

Figure 8: Flow Measurements in Traver Solar System

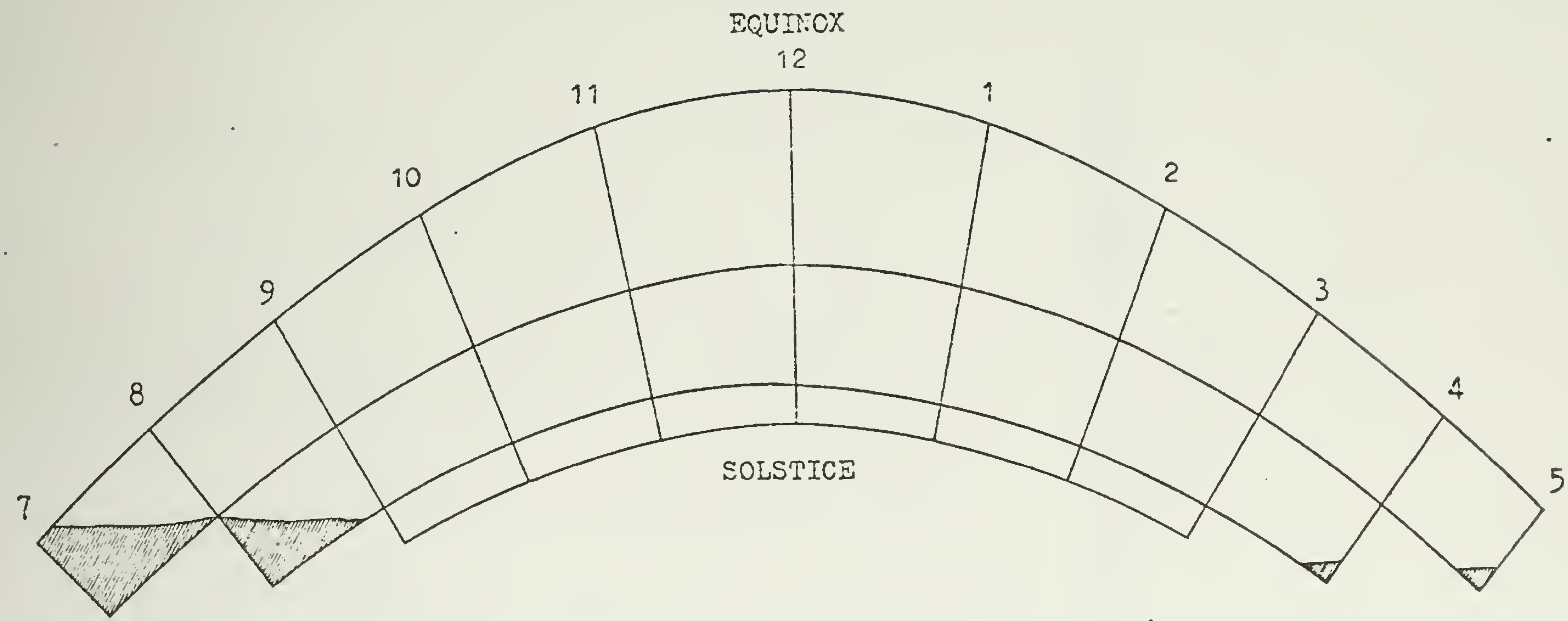


Figure 9: Shading Diagram of Collectors at Traver Site

APPENDIX I

TABLES OF DAILY PERFORMANCE DATA FOR TRAVER HOUSE

```
500 REM *** CALCULATE HOURLY DATA ***
510 S(1)=V(6)\REM COLLECTOR INPUT
511 IF S(1)<.044 THEN S(1)=0
512 IF S(1)<0 THEN S(1)=0
515 S(2)=V(7)\REM COLLECTOR OUTPUT
517 S(3)=8.7*V(1)\REM PASSIVE SOLAR GAIN
518 IF S(3)<0 THEN S(3)=0
520 S(4)=V(9)\REM FURNACE OUTPUT
525 S(5)=(V(2)+V(3))*3.6\REM ELECTRIC INPUT
535 S(7)=.61*((V(12)+V(13))/2-V(17))\REM HEAT LOAD
540 S(8)=(V(12)+V(13))/2\REM HOUSE TEMP
545 S(9)=V(17)\REM AMBIENT
550 S(10)=V(10)\REM CRAWL SPACE TEMP
555 S(11)=V(18)\REM COLLECTOR INLET
556 IF S(11)>S(8)+5 THEN GOSUB 1800
557 IF S(11)<0 THEN GOSUB 1800
558 S(6)=S(2)+S(3)+S(4)+S(5)\REM SUMM INPUT
560 S(12)=V(16)\REM COLLECTOR OUTLET
565 S(13)=V(8)\REM COLLECTOR EFFICIENCY
570 S(14)=V(4)\REM SOLAR FAN STATUS
600 REM *** PRINT HOURLY DATA ***
```

EQUATIONS USED TO PROCESS DATA

DAILY PERFORMANCE SUMMARY FOR THE TRAVER PROJECT 3/ 28/80

HR	COLL INPUT (MJ)	COLL OUTPUT (MJ)	PASSV SOLAR (MJ)	FURN OUTPUT (MJ)	ELECT INPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	CRAWL SPACE (C)	COLL INLET (C)	COLL OUTLET (C)	COLL EFF	SFAN STAT (HRS)
1	.00	.00	.00	10.00	3.20	13.20	13.40	21.24	-.73	4.73	.60	4.63	.00	.00
2	.00	.00	.00	11.18	2.92	14.10	12.94	21.22	.00	4.72	.77	4.26	.00	.00
3	.00	.00	.00	10.01	3.38	13.39	13.20	21.26	-.38	4.79	1.64	4.58	.00	.00
4	.00	.00	.00	11.19	2.48	13.67	14.50	21.12	-2.65	4.30	.62	4.31	.00	.00
5	.00	.00	.00	11.39	3.35	14.74	14.34	21.09	-2.42	3.85	1.26	3.95	.00	.00
6	.00	.00	.00	10.72	2.81	13.53	13.94	21.15	-1.70	4.32	1.52	4.20	.00	.00
7	.06	.00	.00	12.01	3.67	15.68	13.51	21.15	-1.00	4.33	1.29	4.18	.00	.00
8	1.15	.00	.26	10.16	3.42	13.84	13.31	21.45	-.37	4.57	2.22	3.88	.00	.00
9	5.37	.00	1.22	8.86	3.46	13.53	12.45	21.75	1.34	5.37	7.65	4.28	.00	.00
10	12.40	.00	2.78	6.77	2.34	11.89	11.16	22.06	3.77	6.16	17.06	5.08	.00	.00
11	23.18	-.17	5.22	4.19	1.48	10.72	10.02	22.63	6.20	7.64	21.87	16.43	-.01	.14
12	4.95	.03	1.13	.00	5.76	6.92	9.16	21.45	6.44	7.46	16.36	11.56	.00	.02
13	7.90	.00	1.74	.00	5.11	6.85	8.61	20.75	6.64	6.81	12.61	6.56	.00	.00
14	11.45	.00	2.52	.00	4.39	6.92	8.44	21.58	7.74	6.93	16.34	6.44	.00	.00
15	10.86	.00	2.44	.00	6.26	8.70	8.71	22.15	7.87	7.10	16.26	6.61	.00	.00
16	11.14	-.08	2.52	.00	4.86	7.30	9.52	23.11	7.50	7.10	18.58	8.18	-.01	.02
17	5.42	.00	1.22	.00	6.37	7.59	9.31	23.39	8.13	7.36	16.21	7.11	.00	.00
18	2.48	.00	.52	.00	8.42	8.95	9.54	22.46	6.82	6.89	10.76	6.94	.00	.00
19	.28	.00	.09	.00	3.71	3.80	9.77	21.47	5.45	6.29	7.71	6.41	.00	.00
20	.00	.00	.00	.00	2.56	2.56	9.21	19.90	4.80	5.91	5.93	5.89	.00	.00
21	.00	.00	.00	.00	1.94	1.94	8.75	18.83	4.48	5.68	5.34	5.70	.00	.00
22	.00	.00	.00	3.87	3.85	7.72	8.53	18.52	4.53	5.60	5.14	5.49	.00	.00
23	.00	.00	.00	6.20	2.30	8.50	9.18	19.37	4.32	5.62	5.12	5.42	.00	.00
0	.00	.00	.00	4.73	2.59	7.32	9.47	19.30	3.78	5.63	4.82	5.36	.00	.00
	96.64	-.22	21.66	121.28	90.65	233.37	260.95	21.18	3.36	5.80	8.24	6.14	-.00	.18

DAILY PERFORMANCE SUMMARY FOR THE TRAVER PROJECT 3/ 29/80

HR	COLL INPUT (MJ)	COLL OUTPUT (MJ)	PASSV SOLAR (MJ)	FURN OUTPUT (MJ)	ELECT INPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	CRAWL SPACE (C)	COLL INLET (C)	COLL OUTLET (C)	COLL EFF	SFAN STAT (HRS)
1	.00	.00	.00	5.60	2.12	7.72	9.73	19.44	3.49	5.52	4.66	5.48	.00	.00
2	.00	.00	.00	4.68	2.45	7.13	9.87	19.28	3.09	5.53	4.31	5.51	.00	.00
3	.00	.00	.00	5.71	2.41	8.12	10.01	19.32	2.91	5.57	3.83	5.49	.00	.00
4	.00	.00	.00	6.52	1.76	8.28	9.77	19.18	3.16	5.47	3.73	5.22	.00	.00
5	.00	.00	.00	6.42	3.42	9.84	9.81	19.18	3.09	5.37	3.59	5.01	.00	.00
6	.00	.00	.00	8.39	1.94	10.33	9.38	19.08	3.71	5.34	3.77	4.88	.00	.00
7	.08	.00	.00	7.47	3.35	10.82	9.60	19.15	3.41	5.36	3.99	4.99	.00	.00
8	1.04	.00	.26	6.13	3.78	10.17	9.86	19.35	3.19	5.47	4.65	4.98	.00	.00
9	2.91	.00	.61	3.86	5.29	9.76	8.69	20.18	5.94	6.07	8.08	5.40	.00	.00
10	3.78	.00	.87	2.89	4.50	8.26	8.26	20.34	6.79	6.54	11.22	5.90	.00	.00
11	14.02	-.10	3.13	2.81	1.73	7.57	6.90	20.31	8.99	7.80	20.54	7.72	-.02	.02
12	18.77	-.27	4.18	1.93	1.91	7.74	6.19	20.44	10.29	8.77	23.85	14.28	-.01	.11
13	11.19	.00	2.52	1.48	.97	4.98	6.10	20.31	10.30	8.95	21.40	12.01	.00	.00
14	9.24	.00	2.09	.83	3.35	6.27	6.72	20.56	9.55	8.74	19.46	8.88	.00	.00
15	4.73	.00	1.04	2.43	1.26	4.73	6.93	19.98	8.62	8.36	14.55	8.12	.00	.00
16	3.59	.00	.78	2.85	2.59	6.23	7.43	19.93	7.74	8.01	12.68	7.65	.00	.00
17	2.49	.00	.52	4.10	3.53	8.15	8.06	19.61	6.39	7.41	10.02	7.09	.00	.00
18	1.25	.00	.26	8.22	4.54	13.02	9.48	20.03	4.49	6.73	7.90	6.40	.00	.00
19	.00	.00	.00	12.75	8.28	21.03	12.83	22.18	1.15	5.73	3.95	5.60	.00	.00
20	.00	.00	.00	9.77	4.97	14.74	13.19	22.37	.74	5.30	3.12	5.24	.00	.00
22	.00	.00	.00	27.13	3.64	30.77	13.45	21.66	-.40	4.43	1.47	4.36	.00	.00
23	.00	.00	.00	11.43	3.71	15.14	13.82	21.90	-.75	4.44	.81	4.14	.00	.00
0	.00	.00	.00	10.57	2.27	12.84	13.95	21.68	-1.19	4.22	.75	4.00	.00	.00
	73.09	-.37	16.27	153.97	73.76	243.63	220.03	20.23	4.55	6.31	8.36	6.45	-.00	.13

APPENDIX II

DATA ACQUISITION SYSTEM

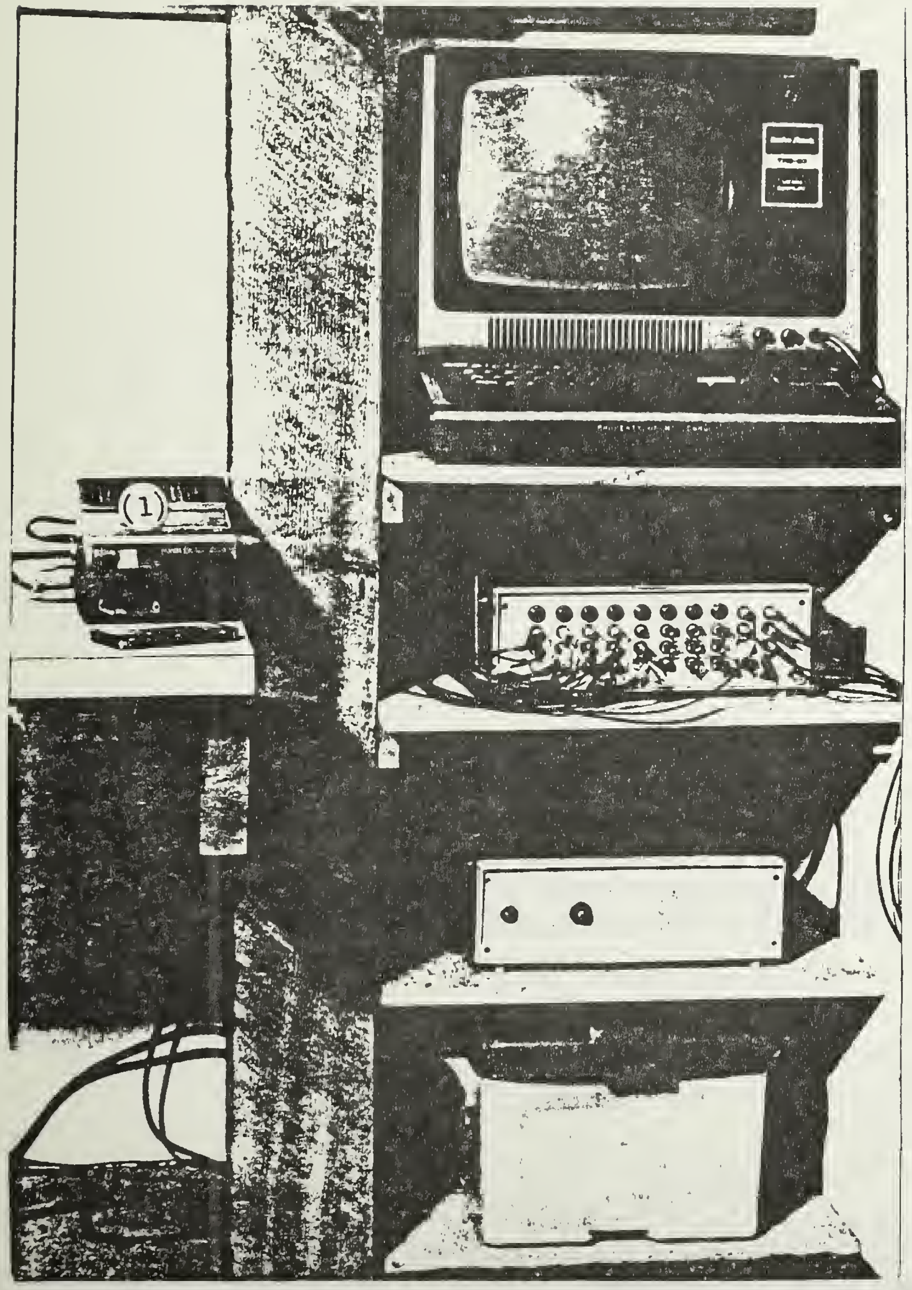
A low cost data acquisition system was developed for solar performance monitoring and is pictured in Figure 1 on the following page. The heart of the system is a Radio Shack TRS-80 computer having a 4K memory. This system has the capability of 40 input channels and is controlled by a Level II BASIC program which allows the user to structure data sampling and processing procedures. Calibration constants, error checks, scan rate, data averaging, printing, etc., can be manipulated using this program capability. A real time clock within the A/D converter chassis is used to time the data output on the cassette. Scanning at an average rate of 40 channels per five seconds, the data is averaged at the end of each hour. This data is then written onto the cassette recorder for processing at a later time.

Temperatures were measured using AD-590 transducers made by Analog Devices. A BASIC computer program was used with the data acquisition system to calibrate the probes against a precision thermometer. The absolute accuracy of the temperatures measured is better than 0.5°C (1°F), while the accuracy of small temperature differences is 0.1°C (0.18°F).

Total solar radiation on the collector surface was measured using a silicon cell pyranometer. The device was manufactured by the contractor and is mounted in the plane of the solar collector. The device has been referenced to NOAA Standards with an estimated overall accuracy of 5%.

Electric power is measured using clamp-on ammeters calibrated on-site against the utility kWh meter. The status of motors, dampers, curtains and fans is determined using appropriate relays, microswitches or mercury switches.

Flow in liquid systems is measured using Hersey MVR-30 turbine meters which have been interfaced to the DAS. Flow in air systems is mapped using a hot-wire anemometer for a one-time measurement to characterize the flow. Status switches and software combine the one-time measurements to calculate appropriate heat flow quantities.



— Video display of current data scan: 40 channels, time, date

— Keyboard for controlling system

(1) Cassette for storing data and programs

— 40 channels analog input, A/D conversion (12 bit), real time clock

— Power supply for computer and A/D interface

— 12V battery: powers system up to 5 hours in the event of a power shortage

Figure 1: Computer-Based Data Acquisition System

THERMAL PERFORMANCE
OF THE HUGHES PASSIVE SOLAR HOUSE

by

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for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM

Grant #RAE-145-800

NOTE ON UNITS

The test results in this report are given in metric or SI units. This convention corresponds to current professional practice and is in accord with the recommendations of the International Solar Energy Society and most technical journals.

Most readers are familiar with the Celsius or Centigrade temperature scale (^{o}C) and with power measured in kilowatts (kW). The metric unit of energy is the Joule (J). Most energy quantities in this report are expressed in megajoules (MJ) which is 10^6 joules or a million joules (1,000 BTU = 1 kBTU = 1.05 MJ). Since one MJ is about one thousand BTU's, a furnace with a rating of 100 thousand BTU/hour would be rated at about 100 MJ/hour. This approximate conversion will be useful to the reader accustomed to thinking in thousands of BTU.

Other abbreviations included in this report are: l = liters, m = meters, m^2 = square meters and kWh = kilowatt hours.

ABSTRACT

This residence is owned by Kurt Hughes and is located about 13 miles south of Miles City, Montana. The house is an earth-sheltered design having a floor area of 114 m^2. The area of the solar aperture is 33m^2. Heat is stored in an interior passive solar wall and in the concrete structure of the house. Auxiliary heat is provided by a wood stove and a heat pump which pumps heat from the ground water.

This system was monitored during December 1979, January and February of 1980. During the monitoring period, the passive solar system provided 50 percent of the heating requirements of the house. Temperature swings of up to 19°C were measured in the sun-space portion of the house. Two systems of movable insulation were used to reduce the heat loss through the solar collector during the night. The performance of the movable insulation and the management of the movable insulation were less than ideal and this reduced the performance of the solar house.

SOLAR COLLECTOR

Type: Passive, sunspace
Aperture Area: 33.3 m^2 (358 ft^2)
Glazing: Double, glass

STORAGE SYSTEM

Passive Wall: 5 MJ-°C^{-1}
Slab: 10.75 MJ-°C^{-1}
Structure: 125 MJ-°C^{-1}

AUXILIARY HEAT

Ground water to air heat pump
Riteway #37 wood stove

BUILDING

Type: Earth sheltered
Floor Area: 114 m^2 (1232 ft^2)
Loss Factor: 0.7 to 0.8 MJhr^{-1} °C^{-1}

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TABLES

FIGURES

1.0 INTRODUCTION

The Hughes residence is located about 13 miles south of Miles City, Montana. The house and the solar system were designed by Mr. Hughes and much of the building was done by Roland Mueller. The house has been occupied from the summer of 1979 until the present.

2.0 DESCRIPTION OF THE HOUSE

Photographs of the exterior of the Hughes passive house are shown in Figure 1. The passive glazing faces due south and is unobstructed. The west and north walls of the house are buried in the earth as shown in Figure 1. The underground portions of the house are constructed of concrete and the above-ground portions are insulated, wood-frame construction.

Figure 2 shows a sectional view of the Hughes house. The solar radiation enters the house through the aperture into a sun-space. An interior passive solar wall made of concrete blocks and containing water-filled plastic pipes separates the sun-space from the rear underground portion of the house. The passive solar wall and the slab floor of the sun-space were designed as heat storage elements. A section detail of the passive solar wall is shown in Figure 2. Figure 3 shows photographs of the solar aperture and an interior view of the sun-space and the passive solar wall. A plan view of the house is shown in Figure 4. The sun-space region is used for the living room and dining room. The underground portion of the house is used for bedrooms and utility room.

2.1 Auxiliary Heat

Auxiliary heat is supplied by a wood stove and a water-to-air heat pump. The heat pump is located in the utility room and ground water is circulated past its condensing coils. Air is drawn from the sun-space through the heat pump and circulated through a duct system to the house. The wood stove, a Rightway Model 37, is located in the living room in the sun-space. The heat pump and the stove are shown in photographs in Figure 5.

The air flow rate through the heat pump was determined by measuring velocities across the duct sections using a hot-wire anemometer. The flow was measured at the inlet duct and the outlet duct of the heat pump and

the average value used to calculate heat output. Figure 6 shows graphs of the velocity distributions in these ducts. The velocity was non-uniform across the section due to elbows in the ducts near the heat pump. The two flow measurements agreed to within four percent.

2.2 Movable Insulation

The solar collector had two systems of movable insulation. The lower half of the window was insulated by foam panels. The panels are shown in the photograph in Figure 7. The panels are constructed of styrofoam bead board 7.5 cm. thick and have a wood frame. The panels are set into a tract built into the window. The panels are installed and removed manually by the owner. The panels are stacked against the wall when they are removed as shown in Figure 7.

The upper half of the solar window is insulated by window quilts. These shades are 0.7 cm. thick and are stored on individual rollers at the top of the window. These shades are operated manually by the owner.

The efficiency and operation of the movable insulation is a very important feature in thermal performance of this house. Temperature probes were placed in the air space between the movable insulation and the glazing for both the upper and lower insulation systems. Knowing this temperature, the house temperature and the outside ambient air temperature allows calculation of the effective heat loss co-efficient through the insulation. Figure 8 shows a schematic of the movable insulation system, the points of temperature measurement and the heat flows. The equation shown in Figure 8 was used on several sets of data to calculate the effective heat loss co-efficient of the curtain. Some typical values of these co-efficients are shown in Table 1. It is important to note that the measured effective heat loss through these curtains is about four times the anticipated heat loss.

The poor performance of the movable insulation appears to be due to the infiltration of air into the space between the insulation and the glazing. An approximate calculation showed that an air velocity due to leakage of only 0.1 m/sec would reduce the effective heat loss from the anticipated design value to the measured value.

2.3 Heat Load

The calculated heat load for the Hughes house is shown in Table 2. The

heat load of the house changes significantly depending on the status of the movable insulation. During the monitoring period, the movable insulation was operated on an irregular schedule. To account for this, heat load factors for each combination of insulating curtain status were used. These values are shown in Table 2. Note that the heat loss factor of the house can change by 25 percent depending on the status of the curtains.

3.0 TRANSDUCER ARRANGEMENT AND CONCEPTUAL MODEL*

Figure 9 shows a schematic section of the Hughes house showing the locations of transducers monitored. Details of the transducer mounting are listed in Table 3. A manual status switch was installed to be operated by the owner when he removed or installed the movable insulation. This proved to be unreliable. The temperature probes between the movable insulation and the glazing were used to determine the status of the movable insulation. We found there were times when the upper or lower or both systems of movable insulation would be open at night or closed during the day when the sun was out. Because of this complicated schedule, the solar input to the house was considered as two parts, the upper solar gain and the lower solar gain. Further, each gain had two values, depending upon whether the movable insulation was in place while the sun was shining or removed. There were, thus, four combinations of solar gain and four combinations of heat loss associated with the aperture.

The wood stove was used during much of the monitoring period. The heat output of the wood stove is difficult to measure accurately. We placed a temperature probe very close to the wood stove so that we would know when there was a fire in the stove. An empirical equation was devised to use this temperature to calculate an approximate heat output from the wood stove.

The heat input from the heat pump was measured by determining the inlet and outlet temperatures and the flow rate through the heat pump. The heat loss from the building was calculated using the heat loss factor multiplied by the temperature difference between the inside house air and the ambient air.

Three heat storage elements were considered. These are shown in Figure 9: the passive slab in the sun-space, the passive solar wall and the remaining underground concrete structure. A temperature probe was

*Instrumentation described in Appendix II

placed on the surface of the slab and this value used to determine passive slab temperature. Three probes were placed inside the passive solar wall and averaged to determine passive wall temperature. A single probe was placed at the rear of the house on the surface of the concrete foundation and insulated to measure the temperature of the surface of the concrete. The thermal masses of these three elements was determined using their dimensions and handbook values for density and specific heat. The hourly heat exchange to or from these three elements was assumed to be the thermal capacity of the element multiplied by its temperature change.

4.0 DATA ANALYSIS AND HEAT BALANCE

The accuracy of the data was assessed by performing a heat balance on the hourly data, the daily data and the monthly data. The basic heat balance equation is shown below:

$$\text{Input Heat} - \text{Stored Heat} = \text{Output Heat}$$

The inputs consisted of solar radiation through the upper and lower portions of the aperture, heat from the wood stove and from the heat pump. Heat could be stored in the passive slab, the passive solar wall and the mass of the house. The heat output depended upon a heat loss factor multiplied by the temperature difference between the house and the outside ambient air.

4.1 Hourly Data

Table 4 is an example of hourly data for January 28. Listed in the table are the hourly values of the energy inputs and outputs, the changes of stored energy and the calculated loss of energy. Also shown in the right-hand section of this table are the temperatures in degrees Celsius of important elements in the house. The table shows hourly values beginning at 1:00 a.m. on the basis of a 24-hour clock. The bottom line of the table shows total energy values summed for the entire day and average temperature values for the day. The column titled SUM INPUT is the sum of the energy inputs and the changes in the stored energy. Next to this column is the CALC LOSS which shows a calculated heat loss of the house during this hour. A comparison of the SUM INPUT and CALC LOSS columns on an hourly basis allows an evaluation of the heat balance equation for the house.

The ambient temperature during the day is seen to be around -15 to -25°C. It is a very cold day. During the early morning hours, heat is delivered to the house from the three storage elements: the passive wall, the passive slab and the mass of the house, as well as the wood stove. Between 6:00 and 7:00 a.m. the heat pump also delivered a small amount of heat to the house. During the day, the upper curtain was open but the lower curtain was closed. The columns UPPER CURT and LOWER CURT are the readings of the temperature probes in the space between the insulating curtain and the glazing. Notice that the temperatures in the lower curtain space reach 78°C due to the solar radiation entering this closed space. Heat is entering the house through the lower insulating curtain due to these high temperatures. This quantity is shown in the LOWER SOLAR column. Notice that the quantity is less than the energy in the UPPER SOLAR column where the insulation has been removed.

During the flow of the day when the sun is shining the stored energy quantities are negative indicating that they are absorbing energy from the sun and from the warm house air. The stove does not operate during this portion of the day. At 1900 hours or 7:00 p.m. the stove is fired and begins putting heat into the house. The storage elements are also cooling down and delivering heat to the house.

Three house temperatures are shown in the table, the temperature of the sun-space, the temperature of the rear underground portion of the house and the average of these two titled HOUSE TEMP. The sun-space is seen to respond more rapidly to the solar radiation as expected.

Hourly data sheets such as these for the entire monitoring period are shown in Appendix I. This hourly data forms the basis of the summary of the performance of this house.

4.2 Summary Data

The hourly data is condensed into daily average values and summaries. The daily summaries for three months are shown in Tables 5, 6 and 7. The format of these tables is similar to the hourly data tables except that the upper and lower curtain temperatures have been replaced by high and low temperatures in the house during that day. The high and low temperature columns show the temperature swing in this house. This is an important feature of passive solar houses. Notice that the temperature swing is normally greater on very clear, sunny days as would be expected.

The heat pump is seen to supply only a small amount of the house heat load excepting during a period from the 24th of December through the 29th. The owner was on a vacation during this period.

The overall performance summary for the entire monitoring period was summarized in Table 8.

5.0 GRAPHICAL DATA

Graphical data is useful in presenting a picture of the performance of this house and is useful during the analysis and data processing phase. A graph of hourly data is presented in Figure 10. This graph covers a time span of five days. The upper part of the graph shows the temperature variations in the passive solar wall, the average house temperature, the underground concrete foundation and the ambient temperature. The lower portion of the graph has three graphs showing the input energies from the sun, the wood stove and the heat pump.

A main feature of this graph is the response of both the house and the ambient temperatures to the solar radiation. The house is seen to warm up each day as the sun comes out and cool during the night. The passive solar wall reaches higher temperatures than the house average air temperature because it is subjected to direct solar radiation. The ambient temperatures were quite low during this period so that the wood stove and the heat pump were used during the night to supply heat to the house.

Figure 11 shows another five-day period of the behavior of the house. During this period there were two sunny days followed by a partially sunny day, then a day with almost no solar radiation and, finally, a clear day. The ambient temperatures during this period averaged around $0^{o}C$ and slightly below so that the heat load on the house was not great. Note that the house ran 100 percent on the solar radiation during the first part of the week and the wood stove was only required during the cloudy period on the fourth day. Note that the large temperature swings in the house occur every day that there is solar radiation and is proportional to the amount of solar radiation.

In Figures 10 and 11, the temperature of the underground concrete is seen to be very stable, changing less than a degree Celsius. The graph in Figure 12 was generated from the same data as the graph in Figure 11.

For this graph, an expanded scale of temperature was used for the underground concrete wall. This scale is shown on the right of the graph. It is interesting to note that the back wall does, indeed, respond to the solar radiation and to the air temperature variations in the house. The air temperatures in the house may change 10 to 20 degrees Celsius but the back wall during the same time may only change one degree Celsius.

A summary graphical presentation of the performance of this house is shown in Figures 13, 14 and 15. This graph shows the average house temperature and the average ambient air temperature on a daily average basis. The lower part of the graph consists of a bar graph showing the energy inputs to the house. Elements of this bar graph include solar energy input, a wood stove energy input and heat pump input on a daily average basis. These graphs are useful in gaining a feeling for the response of this house.

6.0 PREDICTED PERFORMANCE

The annual performance of this house was analyzed using a modified f-chart design procedure. The solar data input is based on a four-year average from Miles City and the weather data consists of long-term averages from Miles City. The heat load factor of the house was an average value which accounted for the insulating curtains. The balance point temperature of the house was assumed to be 18.3 °C (65 °F). The results of the analysis are shown in Table 9.

The f-chart analysis predicts a 46% solar fraction (14,028 MJ solar) during the monitoring period. The measured solar fraction was 49.7% (12,876 MJ solar) for this period. This agreement is well within the assumptions of the design method and the input environmental data. The close agreement is due to the compensating effect of assumed and actual values for house balance point temperature, solar radiation available at the site and ambient temperatures. The design procedure predicts an annual solar fraction of 63% which is judged to be a reasonable value.

TABLE 1

HEAT LOSS OF INSULATING CURTAINS AND PANELS
Sample Data on January 21 - 3 AM

	Temperature, °C			Effective U	
	Ambient	Space	House	kJ/hr m^2 °C	Btu/hr ft^2 °F
[1] Lower Panels	-11.6	3.0	22.95	0.19	1.08
[2] Upper Curtain	-11.6	9.4	22.95	0.09	0.57
[3] Glass				0.12	0.68

[1] Foam, 7.5cm (3in) thick

[2] Reflective, multi layer, on roller

[3] Handbook Value

Note: Figure 8 (page 23) shows the equations used to calculate the Effective U and the transducer arrangement.

TABLE 2

HUGHES HOUSE HEAT LOAD

	R	U (Btu/hr ft^2 ^{o}F)	Area (sq. ft.)	U X A
Ceiling	40	.25	1360	34
Frame Walls	20	.5	460	23
Concrete Walls	60	.0167	560	9
Floor	80	.013	1232	15
Windows	9	.111	29	3
Upper Collectors:				
w/curtains open	1.72	.58	180	104
w/curtains closed	3.6	.278	180	50
Lower Collectors:				
w/curtains open	1.72	.58	180	104
w/curtains closed	2.65	.378	180	68
*Infiltration: 14,300 ft^3 X $\frac{1}{2}$ X .018				129

		Btu/hr ^{o}F	KJ/hr ^{o}C
TOTALS:	Both Upper and Lower Curtains Open	421	0.80
	Only Upper Curtain Open	385	0.73
	Only Lower Curtain Open	367	0.70
	Both Curtains Closed	331	0.63

*Assuming $\frac{1}{2}$ air change/hour

TYPES:

S - SOLAR
T - TEMP
DT - DUCT TEMP
ST - STATUS
P - POWER

TABLE 3
TRANSDUCER LOG

HUGHES HOUSE

DISK #	RS #	PROBE #	TYPE	LOCATION AND MOUNTING
1	1	3	S	Outside Solar Transducer: Mounted on plane of Collector surface
2	2		P	Heat Pump Power: An Amp Clamp in the control box of the Heat Pump
3	3		P	Water Heater Power: An Amp Clamp
5	5	4	S	Inside Solar Transducer: Hung in sun-space area parallel to the Collector surface
6	6		ST	Lower Curtain Status: Manual switch on west wall by Collectors
7	7		ST	Upper Curtain Status: Calculated
8	8		ST	Heat Pump Status: A relay in the Heat Pump control box
9	29	45 46, 47	T	Passive Wall Temperature: A set of three averaging probes inbedded in the Passive Wall
10	30	I O U	T	Heat Pump Temperature Differential: The difference between inlet and outlet temperatures when the Heat Pump is on
11	31	52 53, 54	DT	Heat Pump Inlet Temperature: A set of averaging probes in the Heat Pump inlet duct
12	32	55 56, 57	DT	Heat Pump Outlet Temperature: A set of averaging probes in the Heat Pump outlet duct
13	33	10	T	Sun-space Temperature: A temperature probe hung from the ceiling in the Sun-space Area
14	34	1	T	Back Wall Temperature: A temperature probe on the rear concrete wall
15	35	12	T	Rear House Temperature: A temperature probe hung from the ceiling in the Sewing Room
16	36	13	T	Lower Curtain Temperature: A temperature probe between the lower curtain and glazing
17	37	14	T	Stove Temperature: A temperature probe located near the wood stove to help determine the stove output
18	38	15	T	Concrete Slab Temperature: A temperature probe on the passive concrete storage slab
19	39	17	T	Upper Curtain Temperature: A temperature probe between the upper curtain and glazing
20	40	18	T	Ambient Temperature: A temperature probe at north side of house in a double radiation shield

TABLE 4

EXAMPLE OF HOURLY PERFORMANCE SUMMARY FOR ONE DAY IN JANUARY

DAILY PERFORMANCE SUMMARY FOR THE HUGHES PROJECT 1/ 23 R= 1107

HR	UPPER SOLAR (MJ)	LOWER SOLAR (MJ)	PASS WALL (MJ)	PASS SLAB (MJ)	HOUSE PASS (MJ)	HEAT PUMP (MJ)	STOVE INPUT (MJ)	SUMM INPUT (MJ)	CALC LOSS (MJ)	PASS WALL (C)	PASS SLAB (C)	BACK WALL (C)	SUN SPACE (C)	REAR TEMP (C)	HOUSE TEMP (C)	UPPER CUST (C)	LOWER CUST (C)	AMBT TEMP (C)	HEAT PUMP (MJ)	
1	.0	.0	2.0	1.9	2.5	.0	19.5	25.9	23.4	21.52	17.97	13.65	20.1	16.6	18.4	-4.7	5.2	-26.7	.0	
2	.0	.0	1.9	1.7	3.8	.0	18.4	23.7	23.1	21.14	17.81	13.63	19.2	16.3	17.8	-5.5	4.6	-26.8	.0	
3	.0	.0	2.0	1.7	5.0	.0	19.5	23.2	23.2	20.74	17.65	13.60	19.3	16.1	17.7	-5.9	4.3	-27.1	.0	
4	.0	.0	1.8	1.9	10.0	.0	19.2	32.9	23.4	20.33	17.47	13.56	18.9	15.9	17.4	-6.2	3.9	-27.6	.0	
5	.0	.0	2.0	1.7	10.0	.0	17.8	31.5	23.3	19.97	17.31	13.49	18.0	15.4	16.7	-6.6	3.6	-28.2	.0	
6	.0	.0	1.8	2.4	-6.3	.0	21.5	19.3	23.5	19.64	17.09	13.40	18.5	15.2	16.9	-6.7	3.2	-28.3	.0	
7	.0	.0	1.0	.4	1.3	8.9	30.9	42.3	29.0	19.45	17.05	13.45	20.3	15.9	18.1	-5.9	3.1	-28.0	3.5	
8	.0	.0	-.1	.2	3.8	.5	20.9	25.2	27.2	19.47	17.03	13.44	20.6	15.7	18.1	13.1	5.3	-28.2	.4	
9	15.1	.0	-1.3	-.1	-5.0	.0	18.3	27.0	27.6	19.72	17.04	13.41	23.2	16.0	19.6	24.4	22.5	-26.5	.0	U
10	28.1	6.3	-7.9	-3.2	-11.3	.0	17.9	30.0	26.2	21.30	17.34	13.45	25.0	17.6	21.3	31.6	42.4	-22.4	.0	U
11	35.9	11.8	-11.8	-3.0	-12.5	.0	17.7	39.1	25.4	23.65	17.62	13.56	26.7	18.7	22.7	33.8	58.9	-19.7	.0	U
12	42.0	14.8	-15.7	-3.2	-16.3	.0	.0	21.6	25.0	26.79	17.92	13.64	28.7	19.8	24.2	33.0	69.0	-17.5	.0	U
13	42.4	16.3	-15.9	-3.2	-8.8	.0	.0	30.9	24.9	29.96	18.22	13.77	30.0	20.6	25.3	32.3	74.6	-16.2	.0	U
14	39.9	17.4	-11.7	-2.6	-12.5	.0	.0	30.5	24.8	32.29	18.46	13.84	30.0	21.1	25.9	33.1	78.2	-15.4	.0	U
15	33.2	16.6	-5.2	-2.2	-6.3	.0	.0	36.2	24.8	33.33	18.66	13.94	31.0	21.3	26.1	32.6	76.4	-15.2	.0	U
16	22.2	13.5	-1.6	-1.6	.0	.0	.0	32.5	24.9	33.65	18.91	13.99	29.7	21.3	25.5	30.5	66.5	-15.8	.0	U
17	7.1	6.8	5.0	-.4	5.0	.0	.0	23.5	24.7	32.65	18.95	13.99	26.7	20.2	23.4	26.1	45.2	-17.7	.0	U
18	.0	.0	12.6	1.4	-1.3	.0	.0	12.7	23.9	30.13	18.72	13.98	22.8	18.7	20.7	18.1	23.5	-20.4	.0	U
19	.0	.0	9.3	1.3	-1.3	.0	10.2	19.5	27.6	28.28	18.60	13.96	23.8	18.7	21.2	7.5	17.9	-22.5	.0	
20	.0	.0	5.9	1.3	10.0	.0	11.5	28.7	27.8	27.10	18.43	13.97	23.5	18.5	21.0	3.5	14.1	-23.2	.0	
21	.0	.0	4.9	1.7	6.3	.0	11.5	24.4	28.2	26.12	18.32	13.89	22.6	18.1	20.3	.8	11.2	-24.4	.0	
22	.0	.0	4.9	2.2	1.3	.0	11.3	19.6	28.2	25.14	18.12	13.84	21.6	17.6	19.6	-.9	9.3	-25.2	.0	
23	.0	.0	4.3	2.0	5.0	.0	11.8	23.1	28.5	24.23	17.93	13.83	21.2	17.2	19.2	-2.2	7.9	-26.1	.0	
0	.0	.0	3.4	1.7	5.0	.0	13.2	23.3	29.0	23.60	17.77	13.79	21.4	17.0	19.2	-2.7	7.0	-26.8	.0	
	267.0	103.5	-8.5	4.1	-12.5	9.3	290.8	653.8	654.4	25.0	17.9	13.7	23.5	17.9	20.7	11.4	27.4	-23.2	3.6	

TABLE 5

DAILY SUMMARY OF PERFORMANCE FOR DECEMBER

DAILY PERFORMANCE SUMMARY FOR THE HUGHES PROJECT 12/ 7 R= 3

DA	UPPER SOLAR (MJ)	LOWER SOLAR (MJ)	PASS WALL (MJ)	PASS SLAB (MJ)	HOUSE MASS (MJ)	HEAT PUMP (MJ)	STOVE INPUT (MJ)	SUMM INPUT (MJ)	CALC LOSS (MJ)	PASS WALL (C)	PASS SLAB (C)	BACK WALL (C)	SUN SPACE (C)	REAR TEMP (C)	HOUSE TEMP (C)	LOW TEMP (C)	HIGH TEMP (C)	AMBT TEMP (C)	HEAT PUMP (MJ)
7	.0	.0	11.0	7.3	3.8	.0	.0	22.1	74.0	19.4	17.7	13.8	15.5	16.3	15.9	14.4	16.7	-10.5	.0
8	253.6	204.8	-24.3	-26.4	-55.0	10.0	.0	367.7	340.6	23.1	19.1	13.9	21.2	19.1	20.1	12.3	35.2	.3	14.4
9	151.5	137.6	8.8	-2.7	-37.5	.0	.0	257.7	259.2	23.2	20.4	14.3	21.0	19.0	20.0	15.3	30.5	5.2	1.5
10	2.5	.0	26.5	33.2	23.8	31.6	165.6	283.1	303.2	17.3	18.0	14.4	15.8	16.0	15.9	14.4	17.7	-2.6	13.1
11	262.8	92.7	-22.9	-8.0	52.5	40.0	457.9	875.1	562.0	23.1	17.5	14.0	21.5	18.9	20.2	14.0	34.4	-15.1	15.2
12	161.6	55.9	6.7	4.0	37.5	.0	322.1	537.9	355.8	22.0	17.6	13.7	18.9	18.0	18.4	14.2	29.0	-4.3	.0
13	227.5	227.5	-14.3	-19.0	-33.8	30.5	180.2	593.7	476.6	23.3	18.9	13.6	20.8	18.9	19.8	11.9	34.0	-6.6	11.6
14	101.2	93.6	19.5	13.3	2.5	.0	.0	230.1	267.9	19.7	18.3	13.8	17.3	17.0	17.1	13.4	24.1	1.1	.0
15	.8	.0	-17.3	3.3	63.8	48.9	*298.7	*398.2	524.4	18.3	17.4	13.6	20.9	17.1	19.0	11.7	28.4	-18.5	17.9
16	231.5	230.1	3.5	-11.4	21.3	.0	*200.0	*674.9	754.1	25.2	19.4	13.2	23.2	19.1	21.1	13.9	35.3	-24.5	.0
17	3.2	.7	10.2	14.4	36.3	.0	*150.0	*234.7	248.7	17.1	17.2	13.0	15.8	15.5	15.6	12.0	25.3	-2.5	.0
18	30.8	256.5	-18.3	-30.6	-10.0	.0	.0	228.3	245.1	22.7	20.2	12.9	25.5	20.7	23.1	18.5	35.6	6.9	.0
19	29.6	246.4	3.5	-1.4	-7.5	.0	.0	270.6	332.0	21.8	20.8	13.0	21.9	19.1	20.5	14.5	35.1	-1.4	.0
20	17.6	139.0	14.5	15.1	2.5	.0	.0	183.6	279.2	19.8	19.6	13.0	18.8	17.6	18.2	14.5	27.5	-.1	.0
21	20.8	175.9	1.4	3.7	13.8	.0	* 60.0	*275.4	305.1	19.3	19.3	12.9	18.7	16.9	17.8	13.7	29.7	-2.5	.0
22	6.3	195.6	-21.6	-13.0	-41.3	.0	*200.0	*326.1	392.8	23.0	19.9	12.9	22.2	18.6	20.4	14.1	31.9	-5.8	.0
23	33.5	72.0	15.7	7.8	-20.0	1.9	*100.0	*211.0	351.8	22.9	20.0	13.3	23.3	19.3	21.3	15.1	30.9	-5.8	1.2
24	13.5	39.4	20.9	22.9	32.5	111.9	.0	241.0	234.6	17.0	17.6	13.2	15.6	15.8	15.7	13.7	20.4	-4.5	43.9
25	6.2	22.5	4.0	9.1	30.0	145.7	.0	217.5	218.9	15.2	16.3	13.0	14.9	15.4	15.1	13.9	17.0	-.5	61.3
26	33.5	114.2	-8.2	-4.4	25.0	102.6	.0	267.8	261.4	16.3	16.3	12.7	19.2	16.3	17.7	13.8	30.5	-1.7	40.9
27	37.8	116.0	.0	.1	30.0	127.8	.0	311.6	311.1	16.6	16.3	12.5	19.0	16.2	17.6	13.2	31.8	-5.5	47.0
28	34.6	108.1	-1.1	-.3	16.3	123.6	.0	285.1	291.5	16.7	16.3	12.3	18.9	16.4	17.6	13.3	31.0	-3.9	46.6
29	35.8	114.7	-10.6	-6.3	22.5	100.5	.0	256.6	317.9	17.0	16.4	12.2	20.2	16.7	18.4	13.5	31.1	-5.2	37.6
30	201.1	201.1	-10.2	-12.8	68.8	.0	.0	447.9	450.9	22.2	18.2	12.2	20.6	18.3	19.4	11.8	32.3	-8.7	.2
31	201.9	201.9	-23.4	-18.9	-37.5	.0	.0	324.0	375.7	22.7	19.3	11.4	20.4	18.3	19.4	11.7	33.7	-7.5	.0

TABLE 6

DAILY SUMMARY OF PERFORMANCE FOR JANUARY

DAILY PERFORMANCE SUMMARY FOR THE HUGHES PROJECT 1/ 1 R= 590

DA	UPPER SOLAR (MJ)	LOWER SOLAR (MJ)	PASS WALL (MJ)	PASS SLAB (MJ)	HOUSE MASS (MJ)	HEAT PUMP (MJ)	STOVE INPUT (MJ)	SUMM INPUT (MJ)	CALC LOSS (MJ)	PASS WALL (C)	PASS SLAB (C)	BACK WALL (C)	SUN SPACE (C)	REAR TEMP (C)	HOUSE TEMP (C)	LOW TEMP (C)	HIGH TEMP (C)	AMBT TEMP (C)	HEAT PUMP (MJ)
1	201.9	201.9	6.2	-10.5	-192.5	.0	.0	207.0	214.4	27.0	21.9	13.1	26.8	22.3	24.5	19.3	35.3	4.4	.0
2	.0	.0	7.0	11.7	-112.5	.0	*400.0	*306.2	337.4	21.7	19.9	13.7	22.6	19.4	21.0	16.5	26.8	-3.3	.0
3	18.9	53.7	2.3	1.9	-51.3	.0	*230.0	*310.6	336.1	22.5	19.6	14.5	24.7	20.2	22.4	21.6	29.7	-1.7	.0
4	23.4	201.9	2.0	-4.6	1.3	.0	*200.0	*428.9	486.0	22.4	20.5	14.6	23.7	19.2	21.4	18.7	23.2	-10.5	.0
5	.0	.0	1.4	9.4	16.3	.0	412.3	439.3	414.9	21.8	19.6	14.7	24.0	19.1	21.6	20.2	26.7	-6.5	.0
6	117.5	117.5	-11.6	1.4	27.5	.0	515.2	767.6	650.5	23.1	17.2	14.3	24.2	17.8	21.0	19.1	29.5	-21.6	.2
7	22.4	65.9	18.0	14.6	50.0	.0	369.0	539.9	592.3	21.3	18.2	14.1	22.3	17.5	19.9	18.4	26.7	-23.6	.0
8	93.2	15.4	17.7	19.0	76.3	21.0	414.4	656.9	652.9	19.2	16.9	13.7	20.2	15.8	18.0	13.5	22.8	-26.7	8.1
9	.0	1.1	-13.3	-3.8	-11.3	53.8	506.4	532.9	566.7	18.9	16.3	13.4	21.9	16.5	19.2	20.2	23.3	-22.4	21.2
10	.0	.0	2.7	4.6	100.0	.0	506.6	613.9	529.2	19.4	16.1	13.3	21.6	16.3	19.0	17.5	23.4	-19.4	.0
11	25.3	241.0	-17.8	-27.8	110.0	13.8	500.6	845.0	650.3	21.6	18.0	12.0	24.5	18.6	21.5	18.1	33.1	-21.1	6.1
12	1.2	19.4	-5.1	-3.4	-202.5	.0	390.5	200.0	375.9	22.8	18.5	12.3	24.4	20.2	22.3	17.5	23.0	-3.9	.0
13	166.2	166.5	-.7	-15.7	-76.3	.0	236.7	476.9	338.8	25.5	20.3	13.9	24.7	21.3	23.0	18.8	33.4	2.0	.0
14	102.7	49.4	15.9	18.1	57.5	.0	53.2	276.8	278.5	20.2	19.0	13.7	19.6	18.4	19.0	15.7	25.3	.2	.0
15	242.6	242.6	-24.9	-23.8	28.8	.0	51.3	511.7	434.7	26.2	21.0	13.3	25.3	21.4	23.4	18.8	36.2	-2.3	.0
16	246.4	246.4	1.1	-7.2	-135.0	.0	.0	351.7	408.4	27.0	22.3	13.9	23.9	21.0	22.4	16.3	36.7	-1.4	.0
17	32.9	87.6	29.5	29.0	21.3	.0	6.6	206.8	275.8	21.8	20.2	14.2	19.8	17.8	18.8	15.4	23.5	-3.2	.0
18	.0	.0	-11.5	4.5	46.3	.0	347.2	386.5	364.3	20.4	18.9	14.1	22.9	18.8	20.9	20.4	25.5	-5.5	.0
19	272.7	274.7	-8.5	-19.4	-33.8	.0	229.7	715.5	606.7	26.4	21.0	13.9	24.6	19.9	22.2	15.9	35.1	-15.4	3.6
20	223.4	251.3	5.3	.5	-41.3	4.7	7.3	456.3	486.8	24.4	21.3	14.2	21.5	18.8	20.1	12.2	34.7	-11.5	2.4
21	5.7	13.3	9.1	16.4	5.0	.0	193.5	243.1	318.1	21.1	19.7	14.4	21.8	18.4	20.1	17.2	24.3	-1.9	.0
22	178.8	178.8	-62.2	-47.2	101.3	.0	142.2	291.8	271.3	23.1	20.3	14.4	23.7	19.3	21.5	16.3	33.5	-7.8	.0
27	186.2	192.4	-16.4	-16.8	-10.0	.0	344.6	680.3	492.7	24.2	18.9	13.8	23.1	17.8	20.5	20.4	26.7	-21.3	.0
28	267.0	103.5	-8.5	4.1	-12.5	9.3	270.8	653.9	656.4	25.0	17.9	13.7	23.5	17.9	20.7	18.0	31.0	-23.2	3.8
29	238.4	83.2	4.3	-.8	-7.5	40.2	204.0	566.8	603.3	24.8	17.7	13.7	22.7	17.9	20.3	17.5	32.2	-20.8	17.1
30	259.9	103.8	-9.2	-10.6	-45.0	105.2	122.9	537.0	593.1	26.3	18.5	14.0	24.1	19.5	21.8	15.9	34.6	-18.5	33.7
31	241.4	241.4	-3.9	-22.4	-50.0	.1	229.2	635.9	559.9	26.8	20.6	14.4	25.1	20.0	22.5	18.2	34.7	-12.2	.3

TABLE 7

DAILY SUMMARY OF PERFORMANCE FOR FEBRUARY

DAILY PERFORMANCE SUMMARY FOR THE HUGHES PROJECT 2/ 1 R= 1202

DA	UPPER SOLAR (MJ)	LOWER SOLAR (MJ)	PASS WALL (MJ)	PASS SLAB (MJ)	HOUSE MASS (MJ)	HEAT PUMP (MJ)	STOVE INPUT (MJ)	SUMM INPUT (MJ)	CALC LOSS (MJ)	PASS WALL (C)	PASS SLAB (C)	BACK WALL (C)	SUN SPACE (C)	REAR TEMP (C)	HOUSE TEMP (C)	LOW TEMP (C)	HIGH TEMP (C)	AMBT TEMP (C)	HEAT PUMP (MJ)
1	.0	2.0	18.0	20.3	6.3	.0	112.0	153.5	354.6	20.7	19.2	14.3	20.2	18.1	19.2	13.4	26.1	-5.0	.0
2	251.4	253.9	-23.2	-30.2	-72.5	.0	81.5	460.9	359.4	27.1	21.6	14.8	25.7	21.6	23.7	18.0	36.7	1.5	.0
3	3.4	10.2	33.0	30.2	53.8	.0	.0	135.6	235.0	20.6	20.0	14.8	18.0	18.0	18.0	16.0	21.8	1.5	.0
4	25.2	87.2	-7.1	1.1	11.3	.0	.0	117.6	241.9	21.1	19.2	14.7	23.5	19.4	21.4	16.7	30.8	3.1	.0
5	213.7	213.7	-14.7	-15.6	.0	.0	.0	397.1	375.5	23.1	20.3	14.5	20.7	18.7	19.7	13.6	33.7	-2.5	.0
6	154.5	154.5	10.0	6.3	23.8	.0	.0	354.1	358.0	22.4	20.7	14.4	19.4	18.0	18.7	13.8	29.2	-2.7	.0
7	.0	.0	-9.3	10.6	7.5	.0	231.3	240.2	424.3	21.7	19.2	14.1	24.5	17.2	21.8	22.1	26.8	-6.7	.0
8	149.9	240.5	-5.2	-27.1	-41.0	.0	75.0	391.9	450.1	26.0	21.2	14.5	23.6	20.3	21.9	15.6	33.7	-5.9	.0
9	4.7	38.6	24.3	22.1	52.5	.0	10.4	152.6	276.7	20.2	19.9	14.3	17.9	17.3	17.6	13.9	23.0	-3.5	.0
10	.9	146.5	-10.8	-7.2	1.3	.0	82.2	212.9	258.1	24.9	21.2	14.5	22.5	19.4	21.0	15.4	29.2	-7.6	.0
11	8.4	232.5	-9.4	-20.3	-25.0	.0	59.3	275.5	545.7	25.1	22.7	14.3	23.2	19.1	21.2	13.3	35.4	-12.2	.0
12	.0	.3	9.6	23.1	-5.0	.0	270.5	298.5	414.4	21.8	20.5	14.5	23.0	19.0	21.0	21.1	24.9	-7.5	.0
13	.0	.0	7.5	15.5	40.0	.0	339.7	393.6	434.7	20.4	19.0	14.3	21.9	18.2	20.0	19.8	23.6	-10.1	.0
14	.1	8.5	.7	9.5	41.3	.0	372.7	432.7	490.7	18.7	17.5	13.9	20.7	16.7	18.7	16.7	23.8	-16.1	.0
15	32.6	96.7	23.0	16.7	102.5	11.3	162.5	445.3	476.2	18.1	16.8	13.5	18.6	15.6	17.1	10.9	25.1	-16.6	5.3
16	43.7	141.5	6.5	13.0	83.8	118.0	.0	416.4	462.5	14.0	14.9	12.6	15.4	13.1	14.3	9.0	23.7	-18.9	42.0
17	45.2	123.2	-9.2	-3.3	16.3	110.4	10.7	293.2	370.9	13.5	14.2	12.1	16.6	12.9	14.8	9.2	28.4	-11.4	39.1
18	14.7	123.0	-31.5	-33.8	-136.3	.0	214.6	155.8	360.2	19.7	17.1	12.7	24.1	18.2	21.2	19.1	31.5	-1.1	.0

TABLE 8

OVERALL PERFORMANCE SUMMARY
12/7/79 to 2/18/80

Energy Inputs	Mega Joules	kBtu	%
Solar	12,876	12,204	49.7
Wood Stove	9,512	9,016	36.7
Heat Pump	1,128	1,069	4.4
Electrical	2,376	2,252	9.2
TOTAL	25,892	24,542	100.0

Average Temperatures		°C	°F
Ambient Air		-7.3	18.9
House Air		20.0	68
Temperature Swing:	Front / Rear, Average	13.5 / 5.9	24.0 / 10.6
	Front / Rear, Clear Day	19.0 / 11.5	34.0 / 20.7

TABLE 9

PERFORMANCE PREDICTED BY F-CHART

MON	----DAILY----		----MONTHLY----							
	SOLAR RAD KWh/m2	AMBT TEMP (C)	DEGREE DAYS (C-DAY)	WATER LOAD KWh	HEAT LOAD KWh	TOTAL LOAD KWh	SOLAR FRAC (%)	SOLAR ENERGY KWh	BACKUP ENERGY KWh
JAN	3.3	-8.6	836	0	4071	4071	44	1799	2272
FEB	3.5	-6.5	696	0	3389	3389	57	1946	1443
MAR	3.6	-.6	587	0	2861	2861	73	2082	779
APR	3.2	7.6	322	0	1567	1567	100	1567	0
MAY	2.6	14.1	153	0	747	747	100	747	0
JUN	2.8	18.7	55	0	268	268	100	267	1
JUL	2.9	24.1	3	0	16	16	100	16	0
AUG	3.2	22.6	3	0	16	16	100	16	0
SEP	3.8	16.1	97	0	471	471	100	470	1
OCT	3.9	9.4	279	0	1359	1359	100	1358	1
NOV	2.9	.3	540	0	2631	2631	60	1576	1055
DEC	2.5	-4.9	720	0	3508	3508	36	1265	2243
YEAR	3.2	7.7	4291	0	20904	20904	63	13109	7795

YEARLY SOLAR FRACTION.... .63

CLIENT.................. HUGHES
LOCATION................ MILES CITY

COLLECTOR AREA........... 33.33 m2, 358.6 ft2
COLLECTOR TILT........... 90 DEGREES
COLLECTOR TYPE........... AIR
EFFICIENCY SLOPE......... 3.21 W/C-m2, .56 BTU/F-ft2
Y-INTERCEPT.............. .69
HOUSE LOAD FACTOR........ .20 KWh/C-HOUR, 384 BTU/F-HOUR

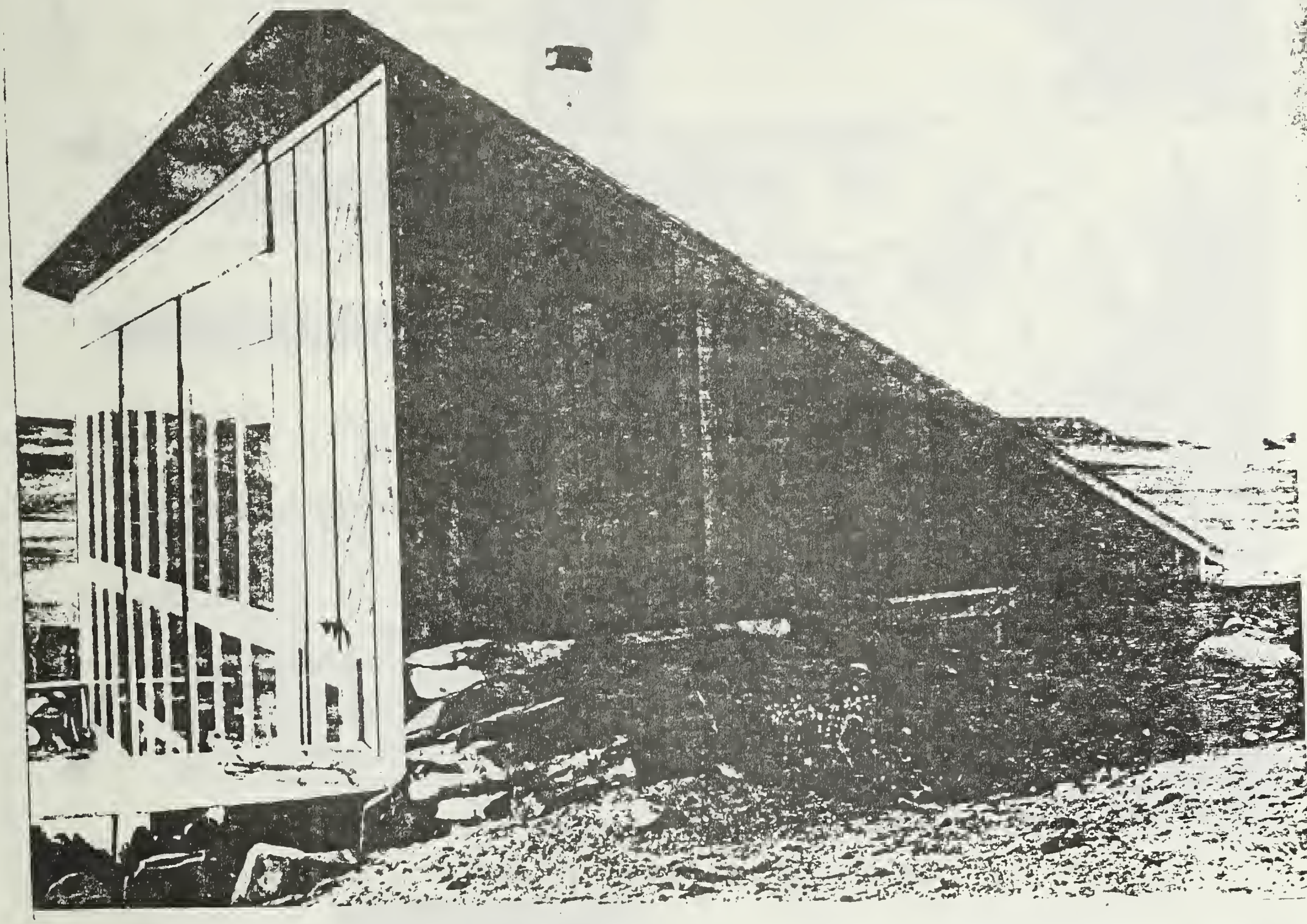
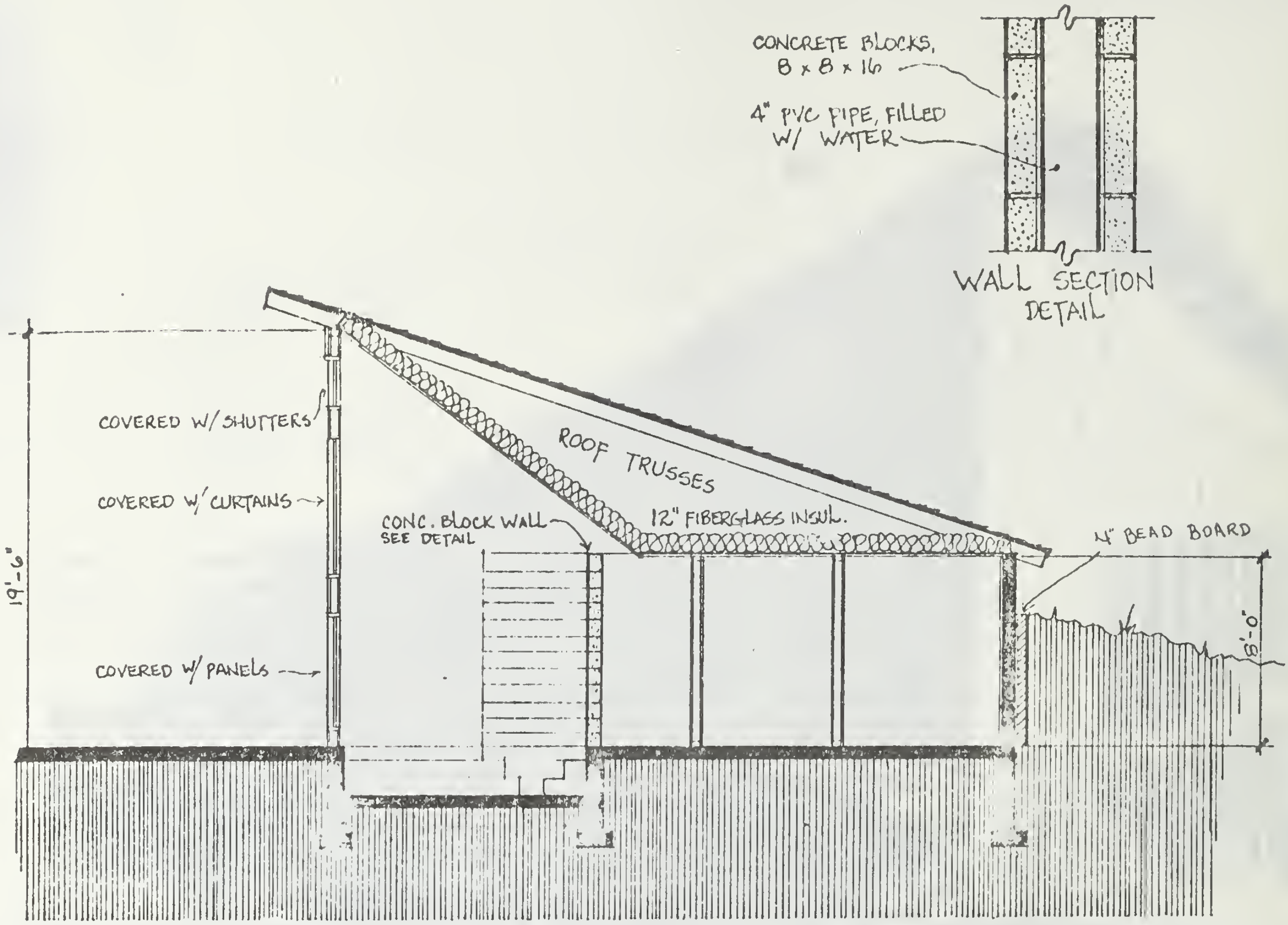
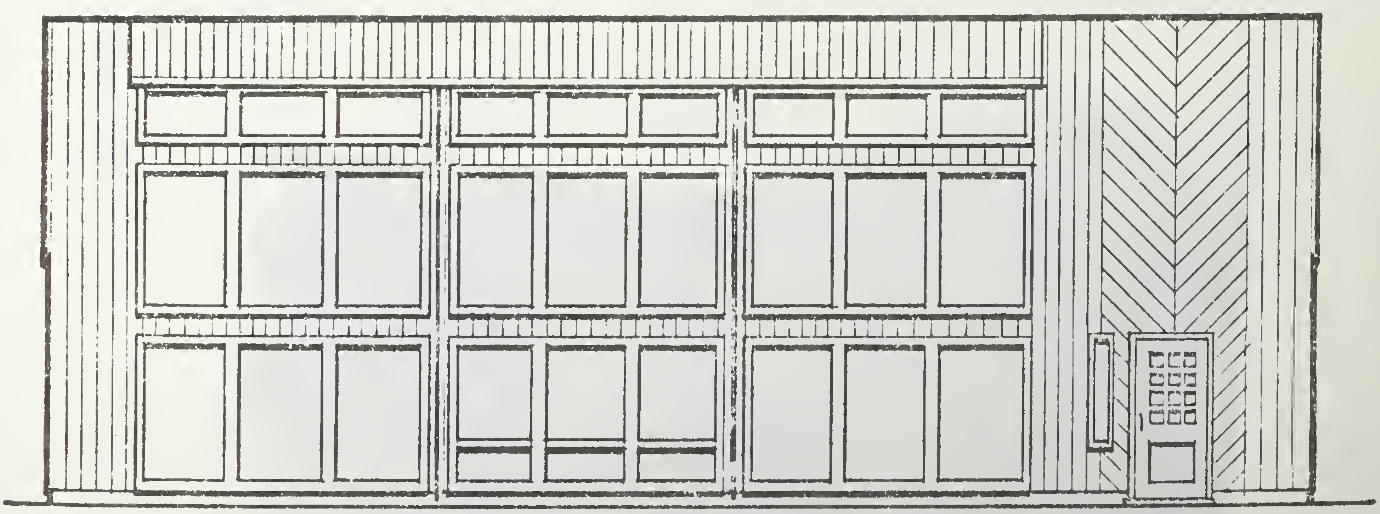


Figure 1:
Photographs of the Outside of the Hughes Passive Solar House



SECTION VIEW @ 1/8" = 1'-0"



SOUTH ELEVATION @ 1/8" = 1'-0"

Figure 2: Cross-sectional View and South Elevation

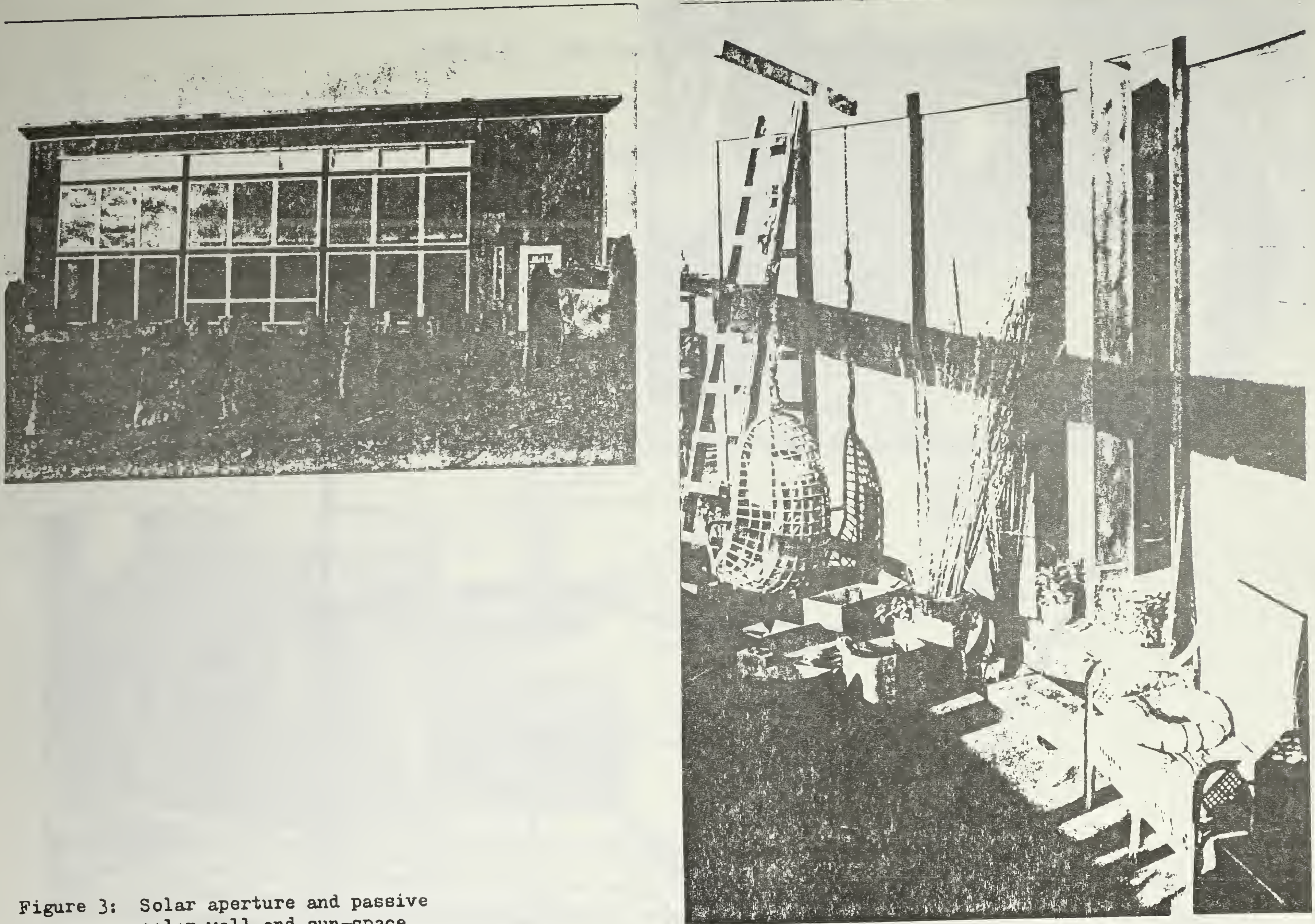


Figure 3: Solar aperture and passive solar wall and sun-space

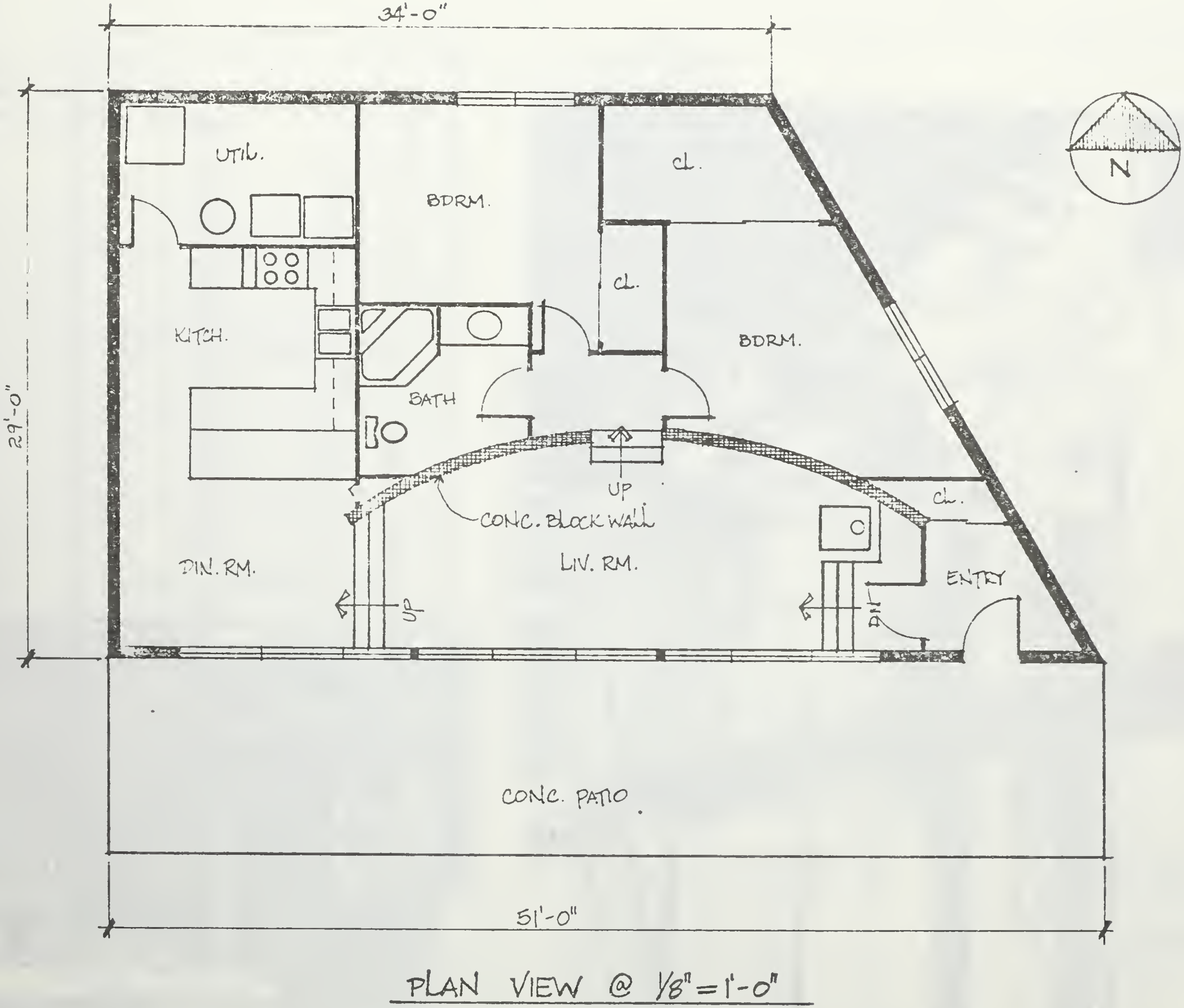
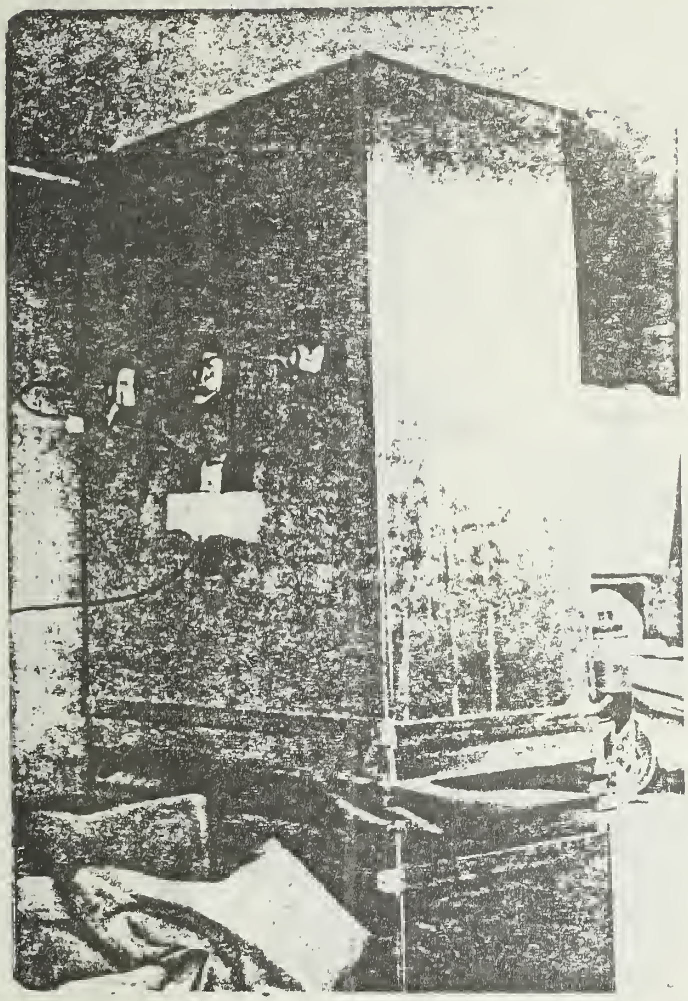


Figure 4: Plan View of Hughes Passive Solar House



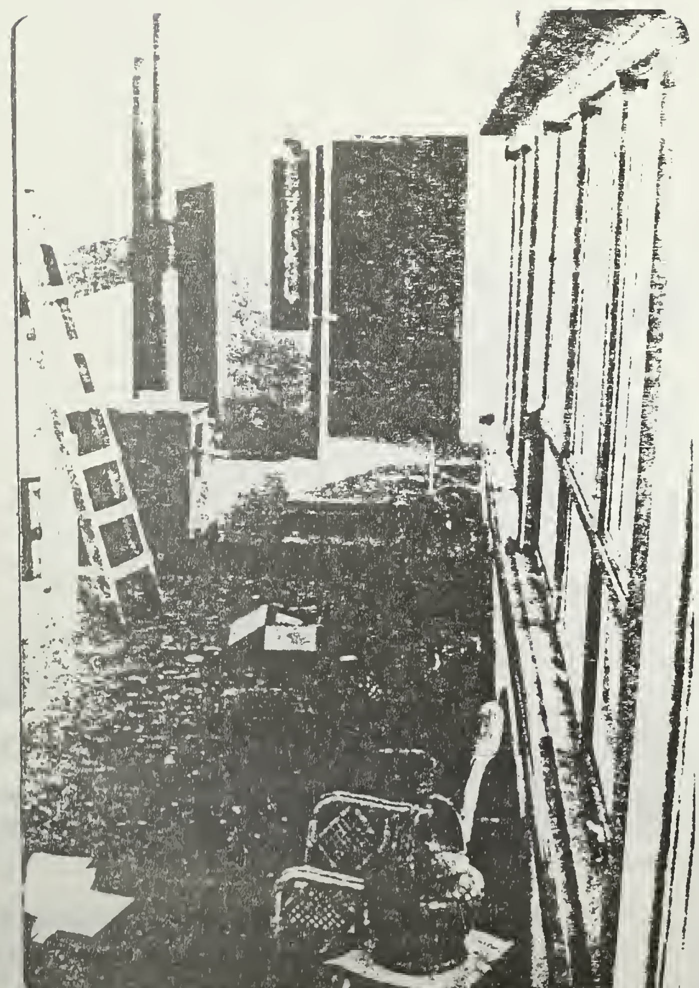


Figure 5: Photographs of Heat Pump and Wood Stove Auxiliary Heating Systems

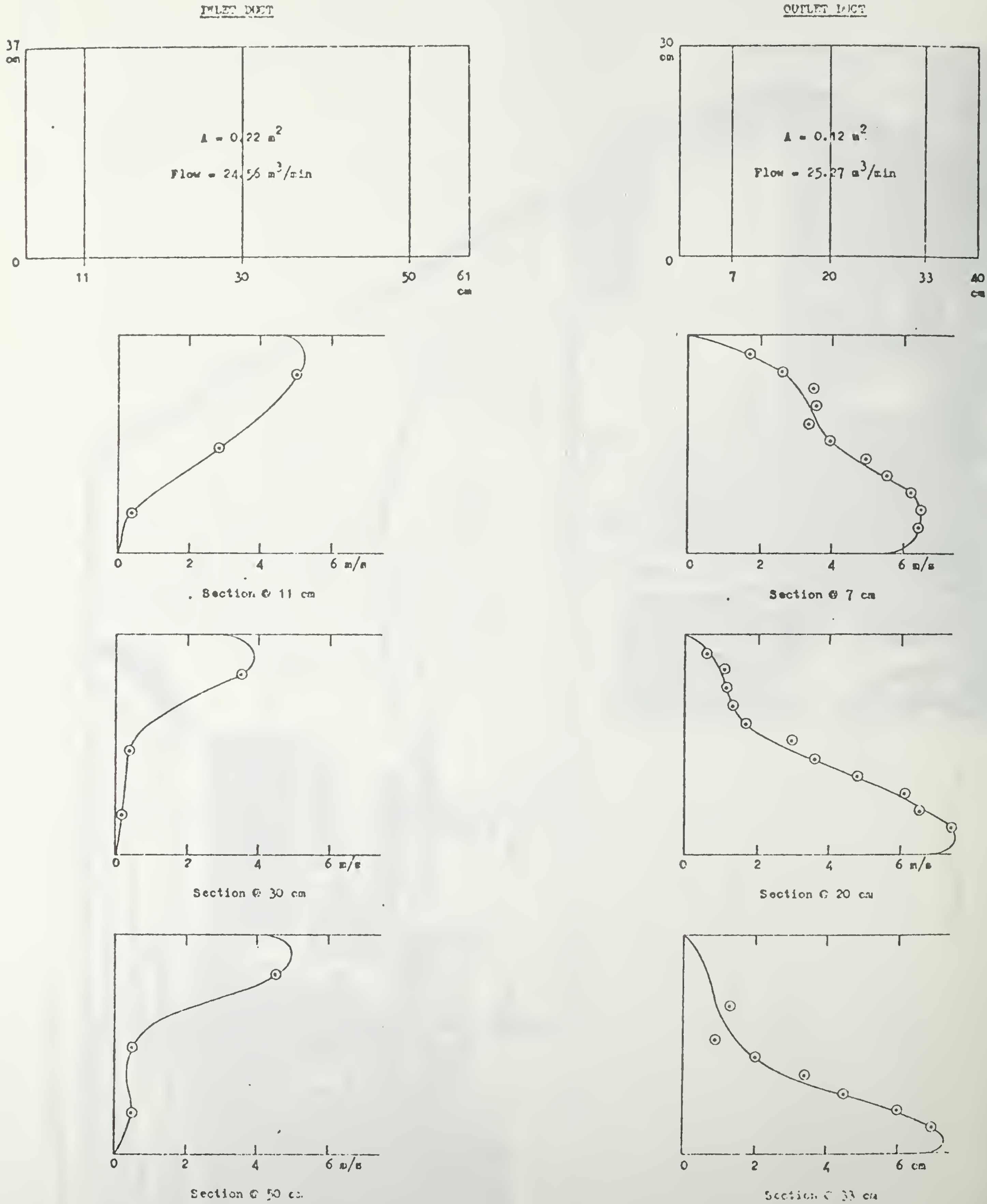


Figure 6: Velocity Distributions in Inlet and Outlet Ducts of Heat Pump

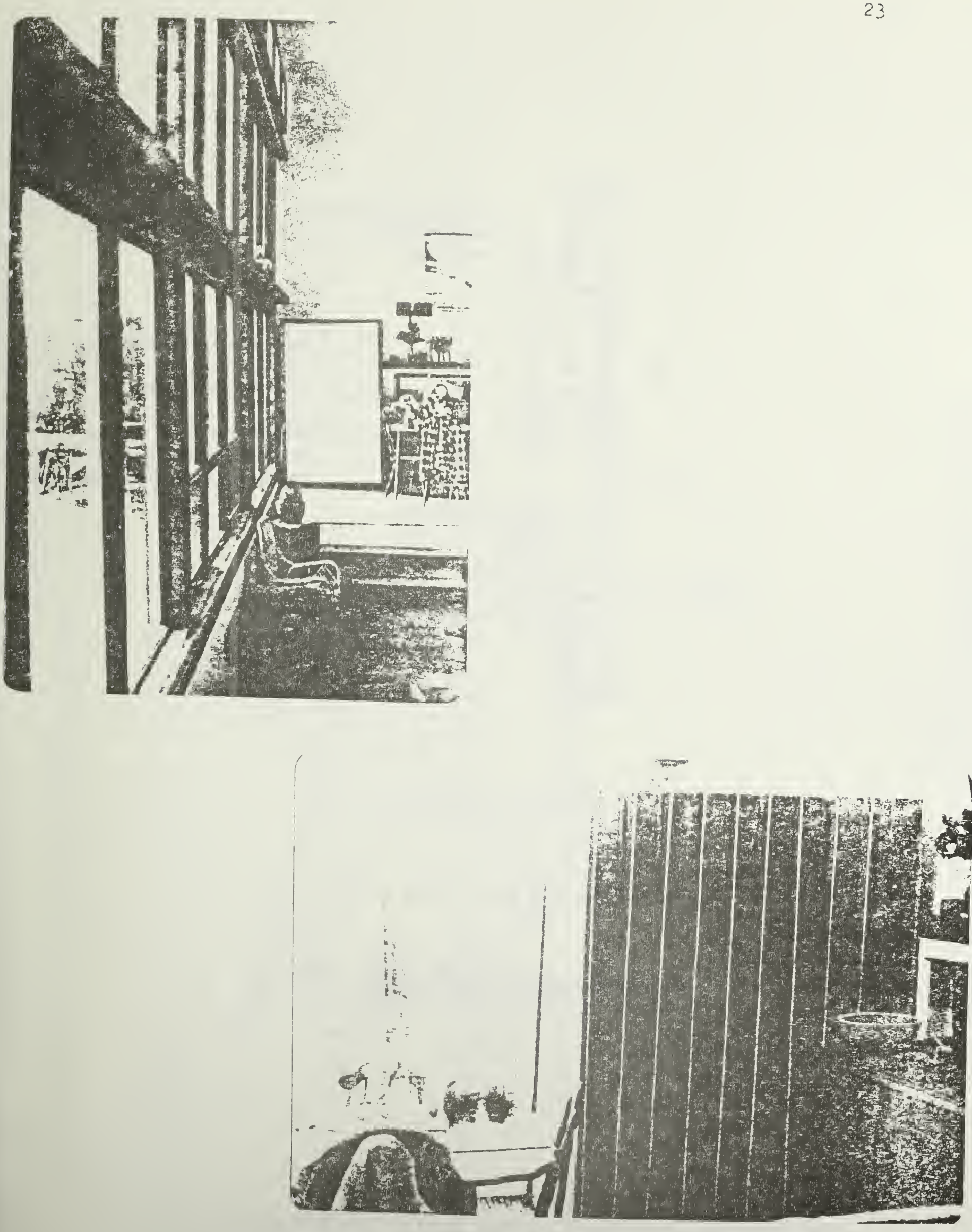
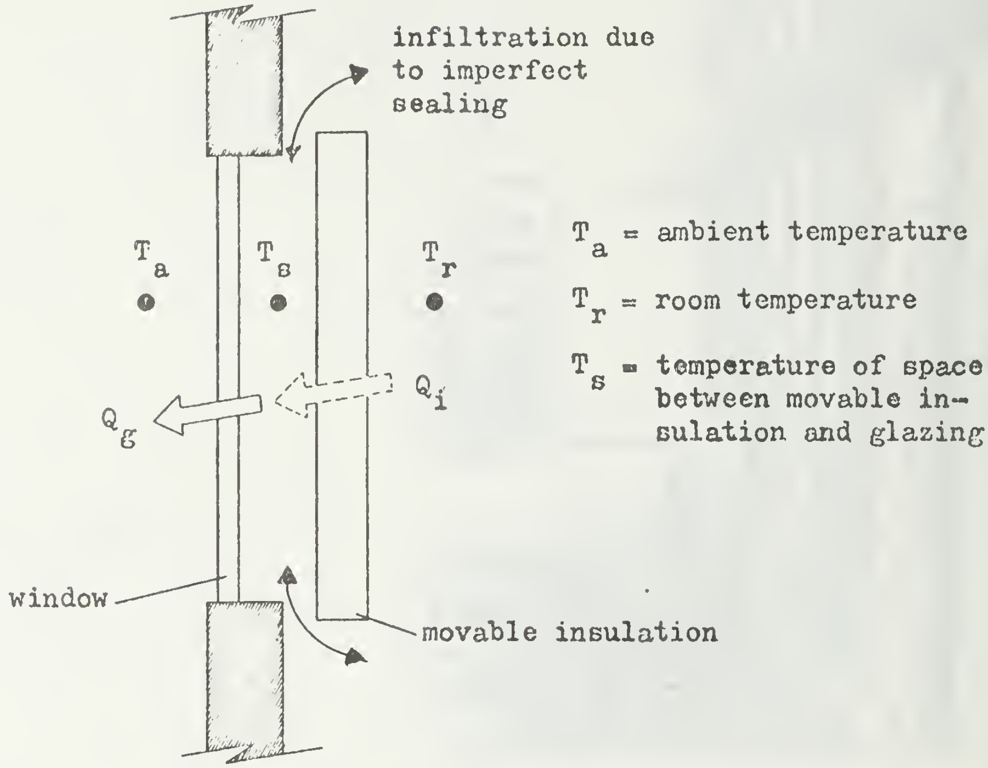


Figure 7: Photographs of Movable Insulation System
for the Lower Part of the Solar Aperture



$$Q_g = Q_i$$

$$U_g * (T_s - T_a) = U_i * (T_r - T_s)$$

$$U_i \text{ (effective)} = \frac{U_g(T_s - T_a)}{(T_r - T_s)}$$

Figure 8:
Schematics and Equations Used to Calculate the Effective
Heat Loss Coefficient for the Movable Insulation

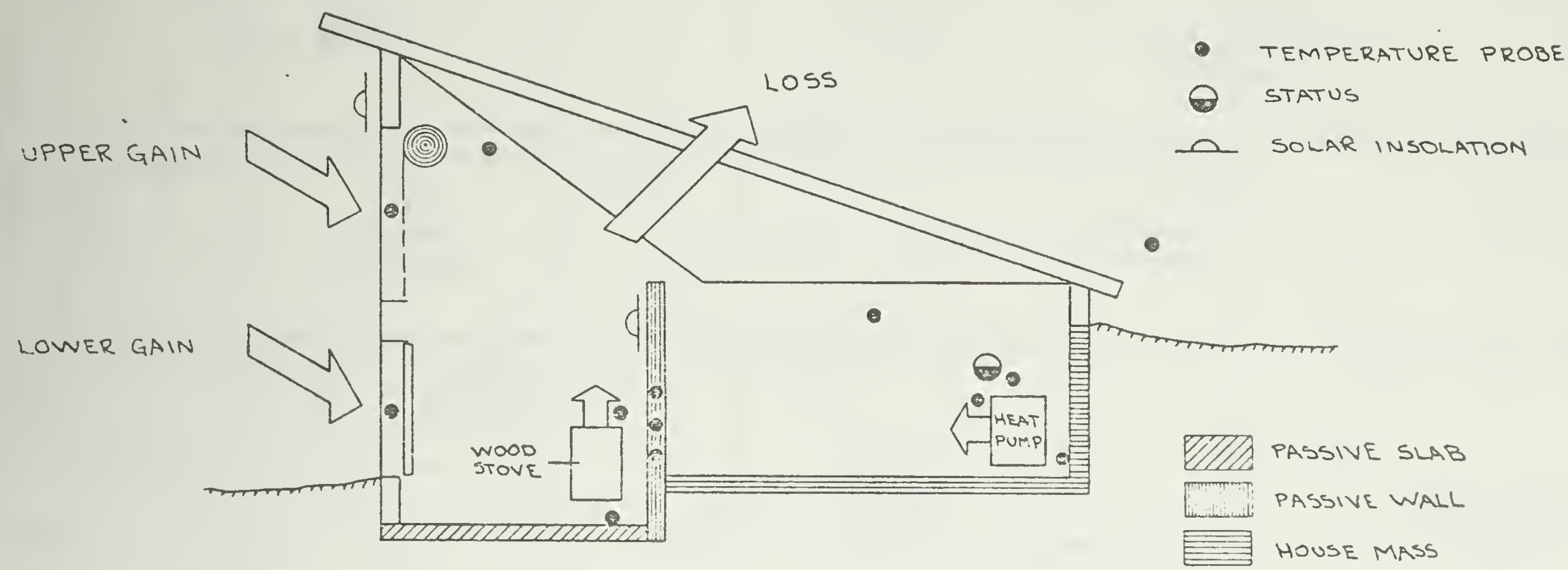


Figure 9:
Cross-Sectional Schematic Showing Locations of Transducers
and Three Heat Storage Elements

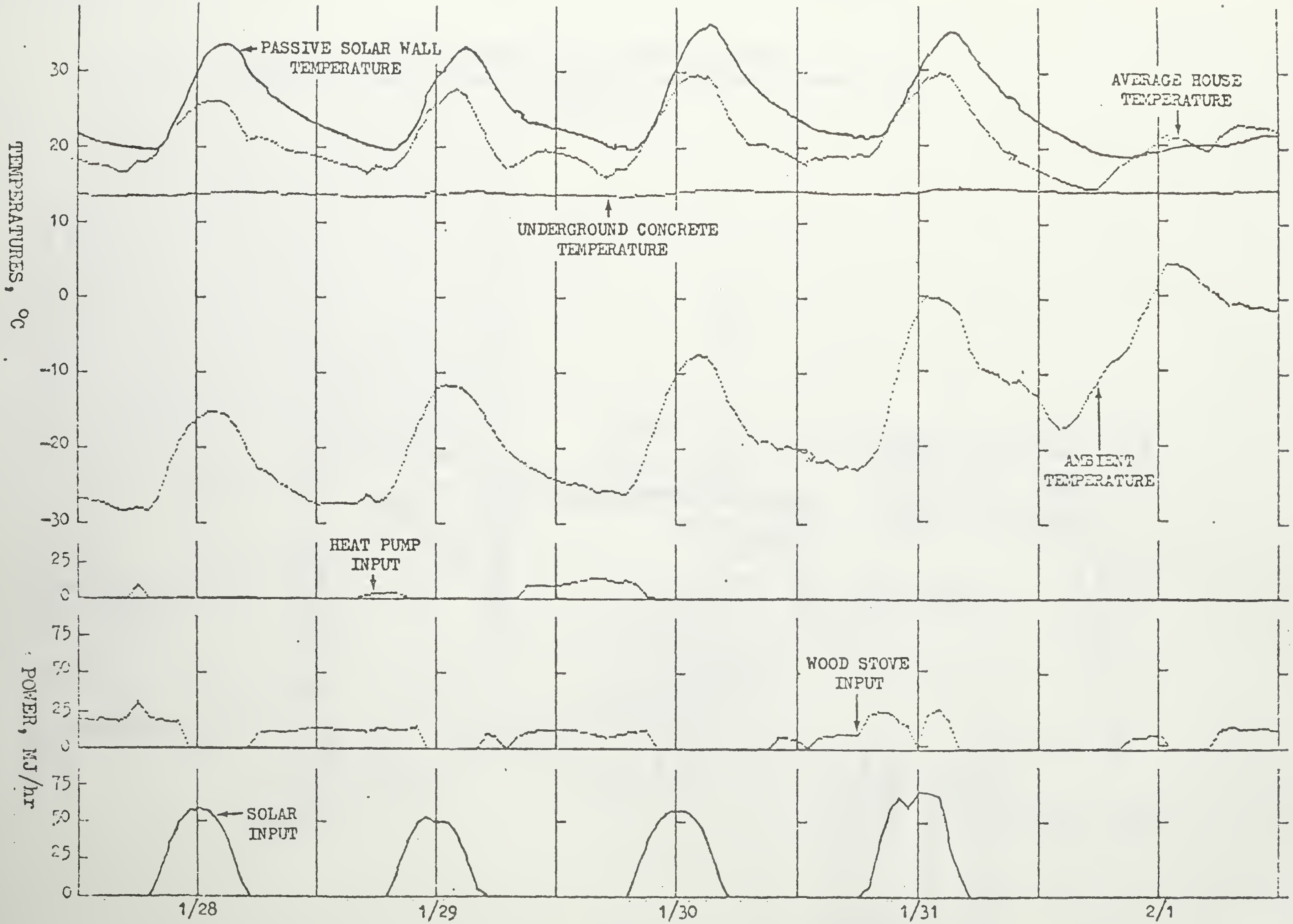


Figure 10: Graphs of Temperature History and Energy Inputs for a Five-Day Period

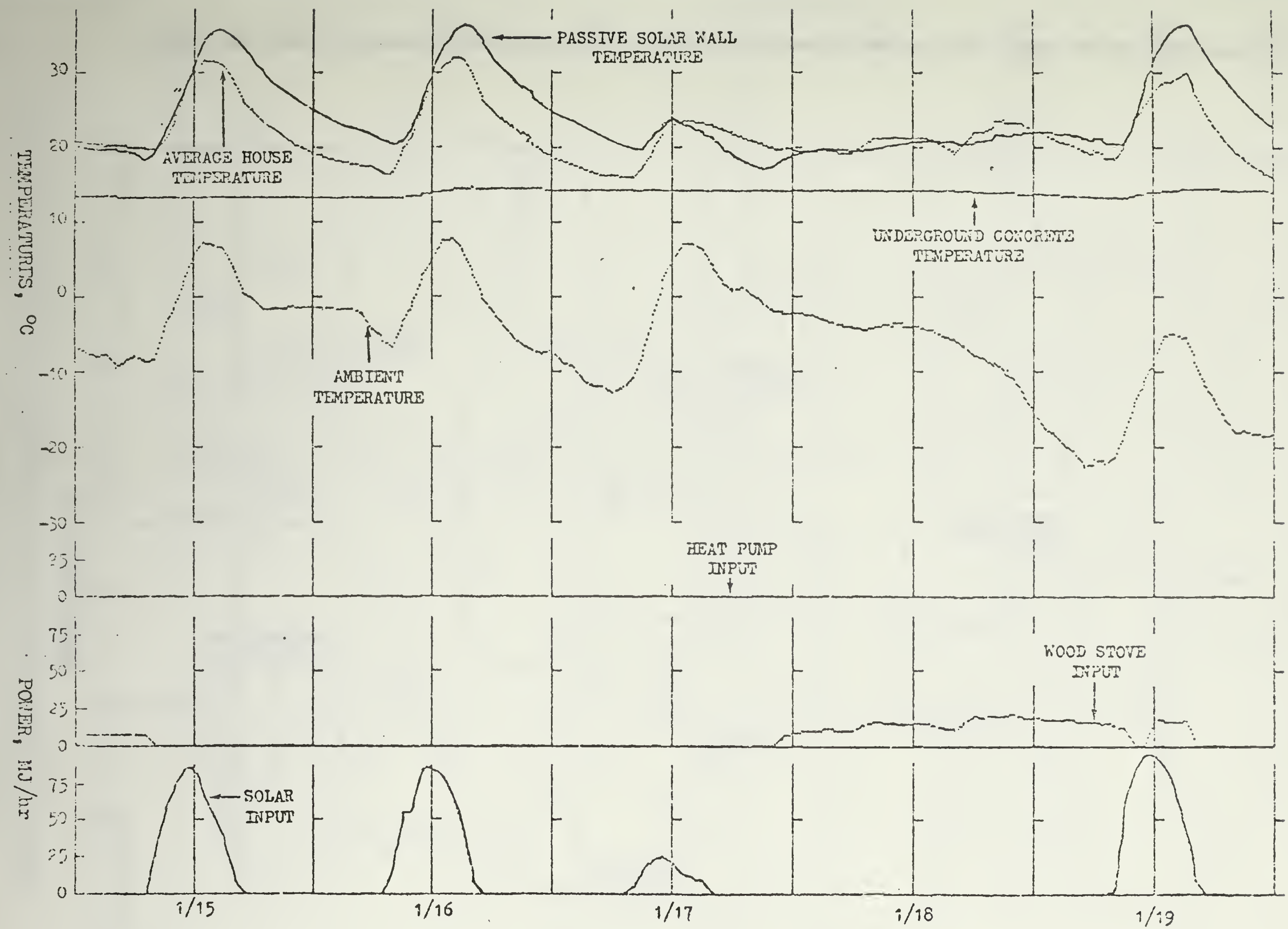


Figure 11: Graphs of Temperature History and Energy Inputs for a Five-Day Period

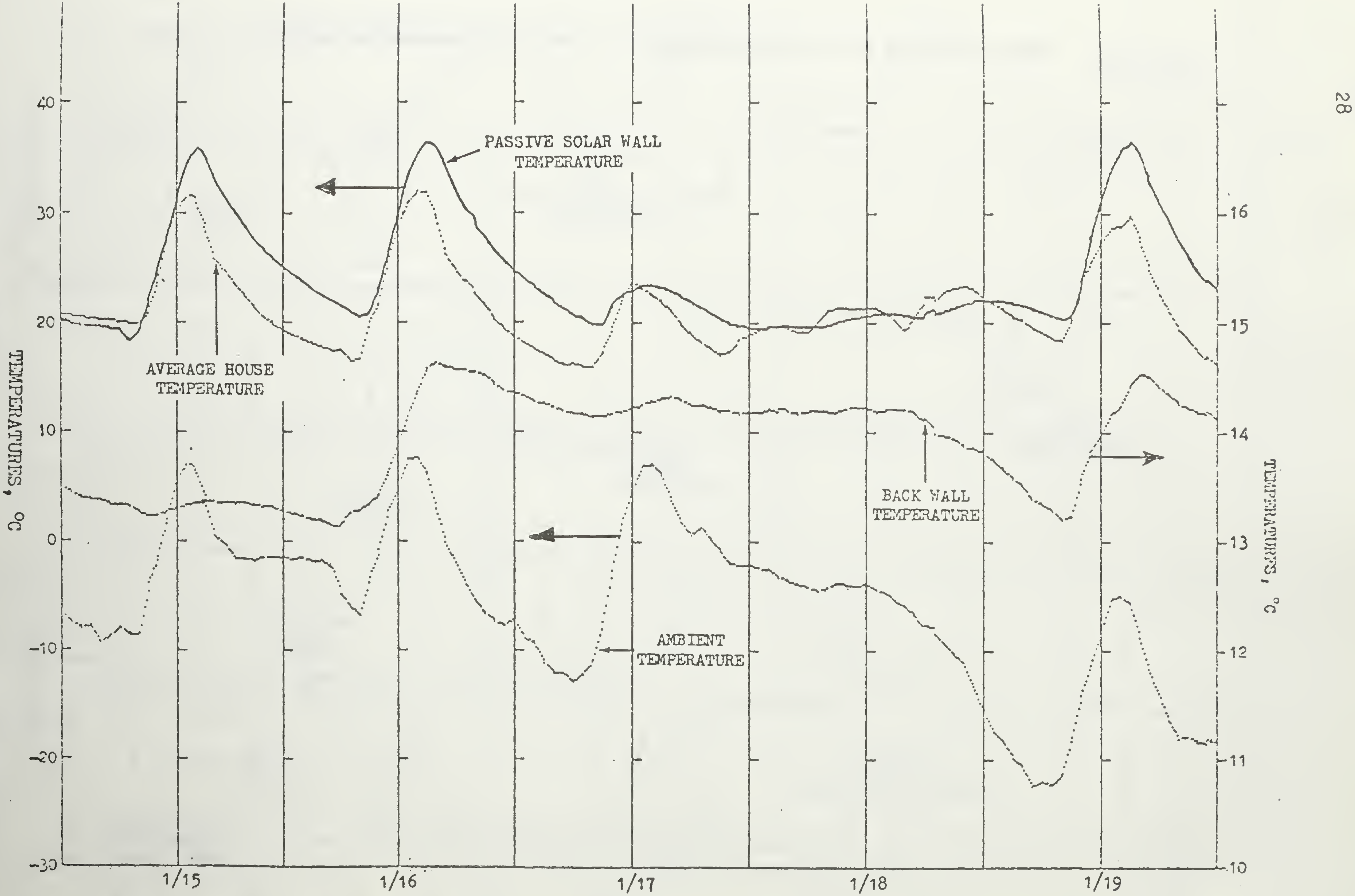


Figure 12: Graph of Temperature History of the Underground Concrete Wall Shown on an Expanded Scale

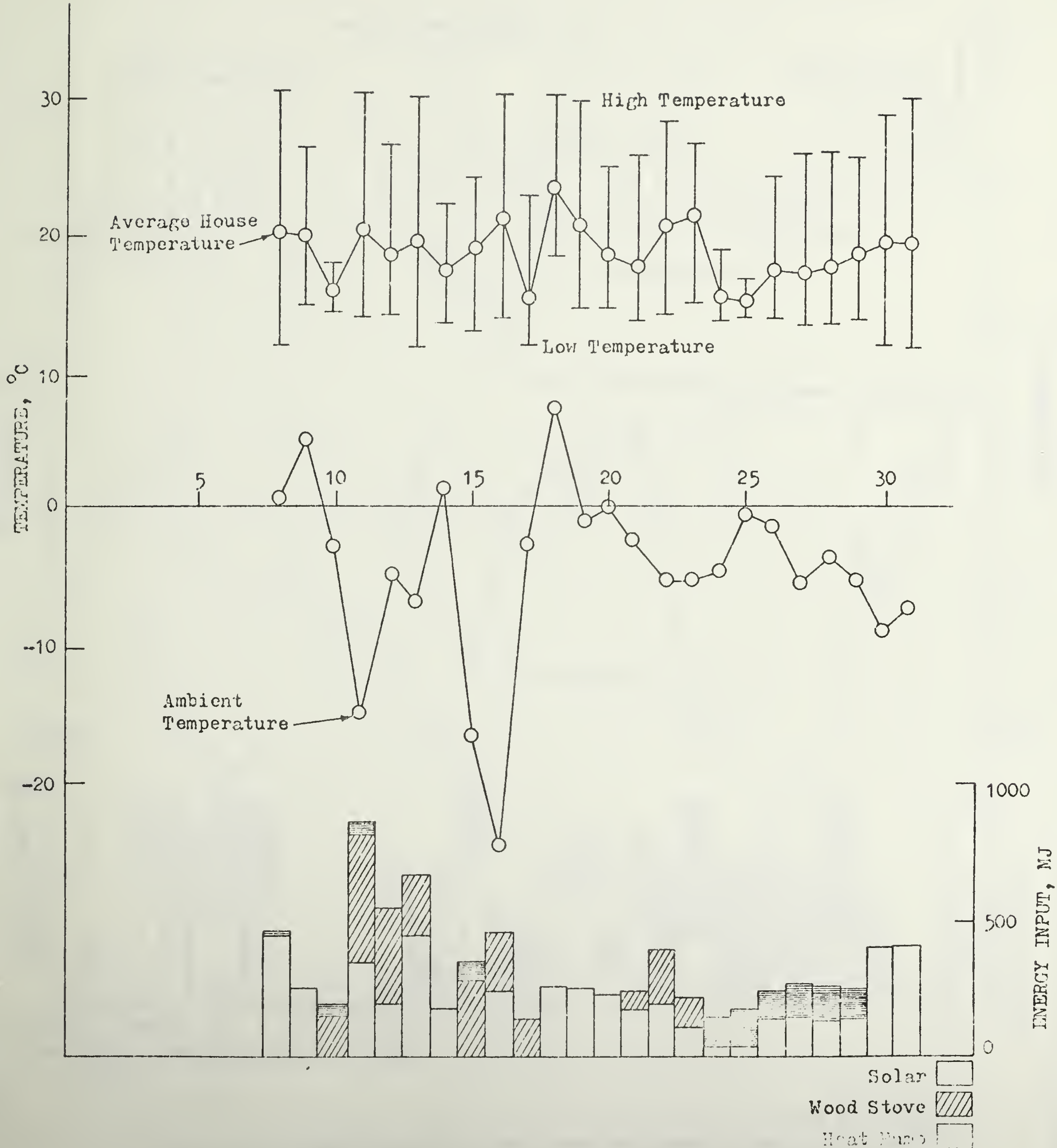


Figure 13: Daily Average Temperatures and Energy Inputs for December

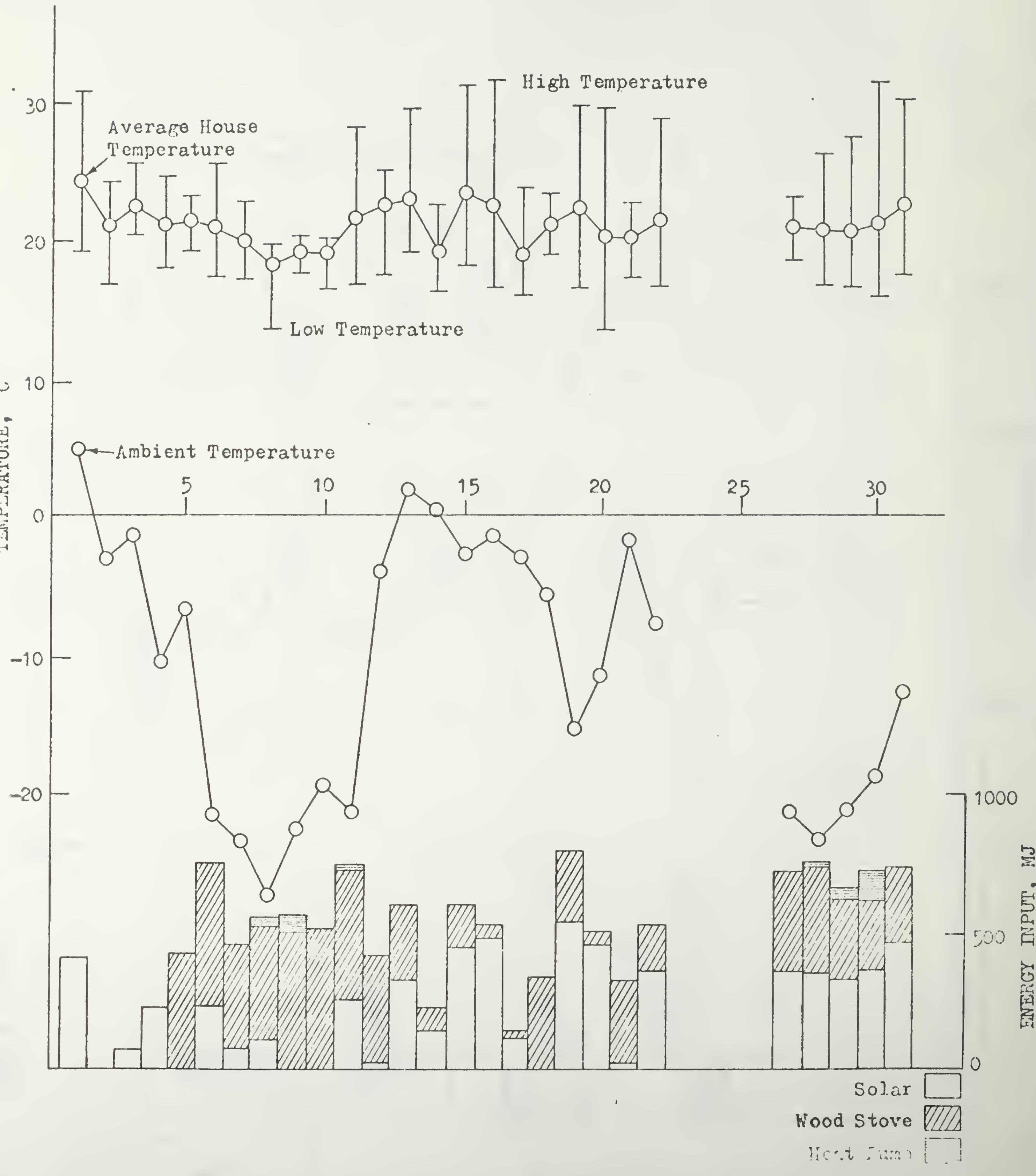


Figure 14: Daily Average Temperatures and Energy Inputs for January

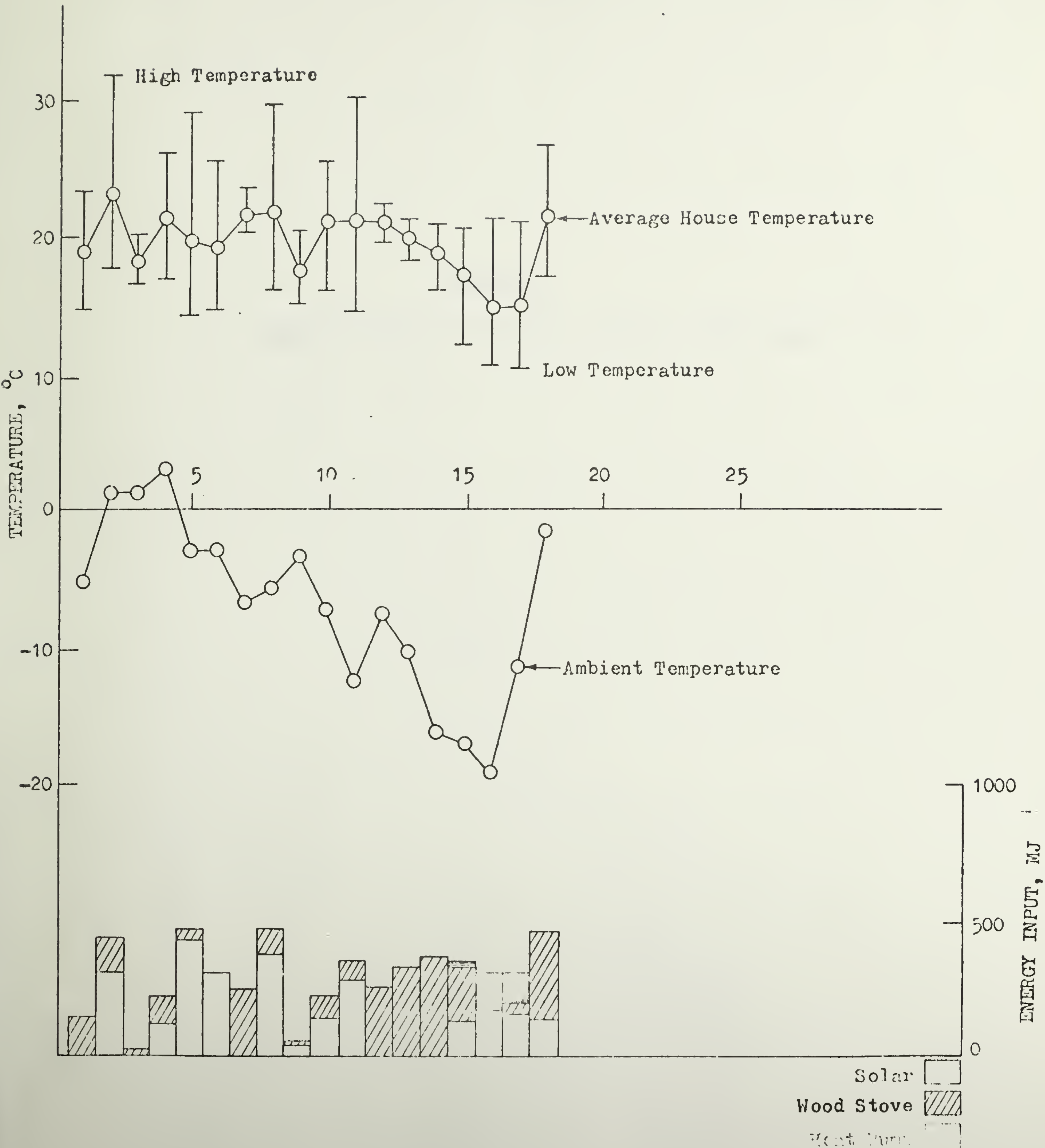


Figure 15: Daily Average Temperatures and Energy Inputs for February

APPENDIX I

TABLES OF HOURLY PERFORMANCE DATA FOR HUGHES HOUSE

```
500 REM *** CALCULATE HOURLY DATA ***
505 IF V(1)<=.01 THEN V(1)=0\IF V(17)>100 THEN V(17)=0\REM ZERO SOLAR AND STOVE
510 IF V(1)>.05 THEN GOSUB 2000 ELSE GOSUB 2100\REM DAY AND NIGHT ROUTINES
512 IF K4=0 THEN B=V(14)
513 IF K4=0 THEN P=V(9)
514 IF K4=0 THEN S=V(18)
515 S(3)=5*(P-V(9))\REM PASSIVE WALL
520 S(4)=10.75*(S-V(18))\REM PASSIVE SLAB
526 GOSUB 3000
530 S(6)=1.83*V(10)\REM HEAT PUMP
535 IF V(17)-V(18)>5 THEN S(7)=1.25*(V(17)-V(18))ELSE S(7)=0\REM STOVE OUT
537 IF V(17)-V(13)<3 THEN S(7)=0
540 S(8)=S(1)+S(2)+S(3)+S(4)+S(5)+S(6)+S(7)\REM SUMM INPUT
550 S(10)=V(9)\REM PASSIVE WALL TEMP
555 S(11)=V(18)\REM PASSIVE SLAB TEMP
560 S(12)=V(14)\REM BACK WALL TEMP
565 S(13)=V(13)\REM SUN SPACE
567 S(14)=V(15)\REM REAR HOUSE
570 S(15)=(V(13)+V(15))/2\REM AVE HOUSE TEMP
575 S(16)=V(19)\REM UPPER CURTAIN TEMP
580 S(17)=V(16)\REM LOWER CURTAIN TEMP
585 S(17)=V(20)\REM AMBT TEMP
590 P=V(9)\B=V(14)+.01*(V(15)-V(14))\S=V(18)\REM PREVIOUS HOUR VALUES
591 IF V(2)<.025 THEN V(2)=0
592 S(19)=3.6*V(2)*2\REM HEAT PUMP
595 K4=1
2000 REM ***** SUBROUTINE TO FIND SOLAR INPUT AND
2010 REM             HEAT LOSS FOR HOURS WHEN THE SUN IS UP *****************
2020 S(9)=(.8-.2*(1-V(7))-.2*(1-V(6)))*((V(13)+V(15))/2-V(20))\REM DAY LOAD
2040 IF V(7)>.5 THEN S(1)=V(1)*41.98 ELSE S(1)=.012*(V(19)-V(13))*16.66
2050 IF V(6)>.5 THEN S(2)=V(1)*41.98 ELSE S(2)=.022*(V(16)-V(13))*16.66
2060 IF S(1)<0 THEN S(1)=0\IF S(2)<0 THEN S(2)=0
2090 RETURN
2100 REM ***** SUBROUTINE TO FIND HEAT LOSS AND FOR NIGHT HOURS *****
2120 S(9)=(.8-.07*(1-V(7))-.1*(1-V(6)))*((V(13)+V(15))/2-V(20))\REM NIGHT LOAD
2170 S(1)=0\S(2)=0\REM ZERO SOLAR
2190 RETURN
3000 REM ****** SUBROUTINE TO LOOK AHEAD FOR STORAGE MASS TEMP ******
3010 R9=R+1
3020 READ#0 %128*R+73,X2
3030 S(5)=(V(14)-X2)*125
3035 !\! X2
3040 RETURN
```

Equations Used to Calculate Hourly Data

TABLE 1

DAILY PERFORMANCE SUMMARY FOR THE HUGHES PROJECT 12/ 8 R= 7

HR	UPPER SOLAR (MJ)	LOWER SOLAR (MJ)	PASS WALL (MJ)	PASS SLAB (MJ)	HOUSE MASS (MJ)	HEAT PUMP (MJ)	STOVE INPUT (MJ)	SUMM INPUT (MJ)	CALC LOSS (MJ)	PASS WALL (C)	PASS SLAB (C)	BACK WALL (C)	SUN SPACE (C)	REAR TEMP (C)	HOUSE TEMP (C)	UPPER CURT (C)	LOWER CURT (C)	AMBT TEMP (C)	HEAT PUMP (MJ)	
1	.0	.0	3.2	2.5	1.3	.0	.0	6.9	17.9	17.65	17.10	13.74	13.8	15.3	14.5	12.7	5.7	-11.1	.0	U
2	.0	.0	2.9	2.3	1.3	.0	.0	6.4	17.9	17.03	16.87	13.73	13.3	14.9	14.1	12.2	5.3	-11.5	.0	U
3	.0	.0	2.3	2.2	3.8	.6	.0	8.8	17.4	16.62	16.69	13.72	13.1	14.7	13.9	12.1	5.0	-10.9	.9	U
4	.0	.0	2.2	1.8	3.8	.9	.0	8.7	17.6	16.19	16.52	13.69	12.8	14.5	13.7	11.8	4.7	-11.5	1.4	U
5	.0	.0	2.1	1.8	2.5	1.2	.0	7.5	17.6	15.78	16.35	13.66	12.5	14.4	13.4	11.6	4.4	-11.7	1.7	U
6	.0	.0	1.9	1.7	3.8	1.2	.0	8.5	17.2	15.41	16.19	13.64	12.4	14.3	13.3	11.6	4.2	-11.2	1.7	U
7	.0	.0	1.7	1.5	1.3	1.4	.0	5.8	16.6	15.08	16.05	13.61	12.3	14.2	13.2	11.5	4.3	-10.6	2.0	U
8	.0	.0	1.6	1.5	2.5	1.4	.0	7.0	16.5	14.76	15.91	13.60	12.5	14.2	13.3	11.6	5.5	-10.2	2.0	U
9	24.3	.4	-1.0	-.3	-2.5	.0	.0	20.9	14.0	14.95	15.94	13.58	17.2	14.7	15.9	17.7	18.1	-7.4	.0	U
10	30.2	.5	-6.2	-8.3	-1.3	3.2	.0	18.2	13.1	16.19	16.71	13.60	20.4	16.5	18.5	21.1	21.7	-3.2	4.7	U
11	39.5	37.5	-27.9	-40.4	-5.0	.0	.0	5.7	14.1	21.76	20.47	13.61	26.0	19.8	22.9	27.7	27.7	5.3	.0	B
12	41.1	41.1	-16.3	.4	-12.5	.0	.0	53.9	12.6	25.02	20.43	13.65	28.4	21.3	24.9	30.2	29.7	9.1	.0	B
13	41.1	41.1	-20.3	-10.8	-8.8	.0	.0	42.5	11.6	29.07	21.43	13.75	31.4	23.5	27.5	33.2	31.8	13.0	.0	B
14	37.8	37.8	-14.3	-22.5	-11.3	.0	.0	27.5	12.8	31.93	23.52	13.82	33.9	26.0	27.9	35.4	33.3	13.9	.0	B
15	29.8	29.8	-9.8	5.3	-8.8	.0	.0	46.4	13.3	33.88	23.03	13.91	35.2	26.6	30.9	36.2	33.5	14.2	.0	B
16	14.7	14.7	-1.4	12.6	-8.8	.0	.0	31.9	13.6	34.15	21.95	13.93	34.0	26.2	30.1	34.2	31.5	13.0	.0	B
17	.0	.0	5.9	4.0	-11.3	.0	.0	-1.4	14.8	32.93	21.49	14.05	30.2	24.4	27.3	27.2	27.7	8.8	.0	B
18	.0	.0	11.3	3.8	-5.0	.0	.0	10.1	13.8	30.72	21.14	14.14	26.3	22.9	24.6	25.3	22.8	5.6	.0	U
19	.0	.0	9.4	3.1	-3.8	.0	.0	8.7	12.6	28.85	20.85	14.18	23.8	21.8	22.8	22.8	18.8	4.7	.0	U
20	.0	.0	7.5	3.0	2.5	.0	.0	13.0	12.1	27.35	20.57	14.21	21.9	20.8	21.3	20.9	16.6	4.1	.0	U
21	.0	.0	6.2	2.4	-2.5	.0	.0	6.1	11.9	26.11	20.35	14.19	20.6	20.0	20.3	19.7	15.1	3.2	.0	U
22	.0	.0	5.7	2.2	2.5	.0	.0	10.4	11.4	24.97	20.15	14.21	19.7	19.3	19.5	18.8	14.0	3.2	.0	U
23	.0	.0	5.0	2.0	-3.8	.0	.0	3.2	10.2	23.93	19.96	14.19	18.9	18.8	18.9	18.2	13.4	4.4	.0	U
0	.0	.0	4.3	1.8	5.0	.0	.0	11.1	10.0	23.13	19.79	14.22	18.5	18.7	18.6	17.7	12.7	4.2	.0	U
	259.6	204.8	-24.3	-26.4	-55.0	10.0	.0	357.7	340.6	23.1	19.1	13.9	21.2	19.1	20.1	21.0	17.0	.3	14.4	

APPENDIX II

DATA ACQUISITION SYSTEM

A low cost data acquisition system was developed for solar performance monitoring and is pictured in Figure 1 on the following page. The heart of the system is a Radio Shack TRS-80 computer having a 4K memory. This system has the capability of 40 input channels and is controlled by a Level II BASIC program which allows the user to structure data sampling and processing procedures. Calibration constants, error checks, scan rate, data averaging, printing, etc., can be manipulated using this program capability. A real time clock within the A/D converter chassis is used to time the data output on the cassette. Scanning at an average rate of 40 channels per five seconds, the data is averaged at the end of each hour. This data is then written onto the cassette recorder for processing at a later time.

Temperatures were measured using AD-590 transducers made by Analog Devices. A BASIC computer program was used with the data acquisition system to calibrate the probes against a precision thermometer. The absolute accuracy of the temperatures measured is better than 0.5°C (1°F), while the accuracy of small temperature differences is 0.1°C (0.18°F).

Total solar radiation on the collector surface was measured using a silicon cell pyranometer. The device was manufactured by the contractor and is mounted in the plane of the solar collector. The device has been referenced to NOAA Standards with an estimated overall accuracy of 5%.

Electric power is measured using clamp-on ammeters calibrated on-site against the utility kWh meter. The status of motors, dampers, curtains and fans is determined using appropriate relays, microswitches or mercury switches.

Flow in liquid systems is measured using Hersey MVR-30 turbine meters which have been interfaced to the DAS. Flow in air systems is mapped using a hot-wire anemometer for a one-time measurement to characterize the flow. Status switches and software combine the one-time measurements to calculate appropriate heat flow quantities.

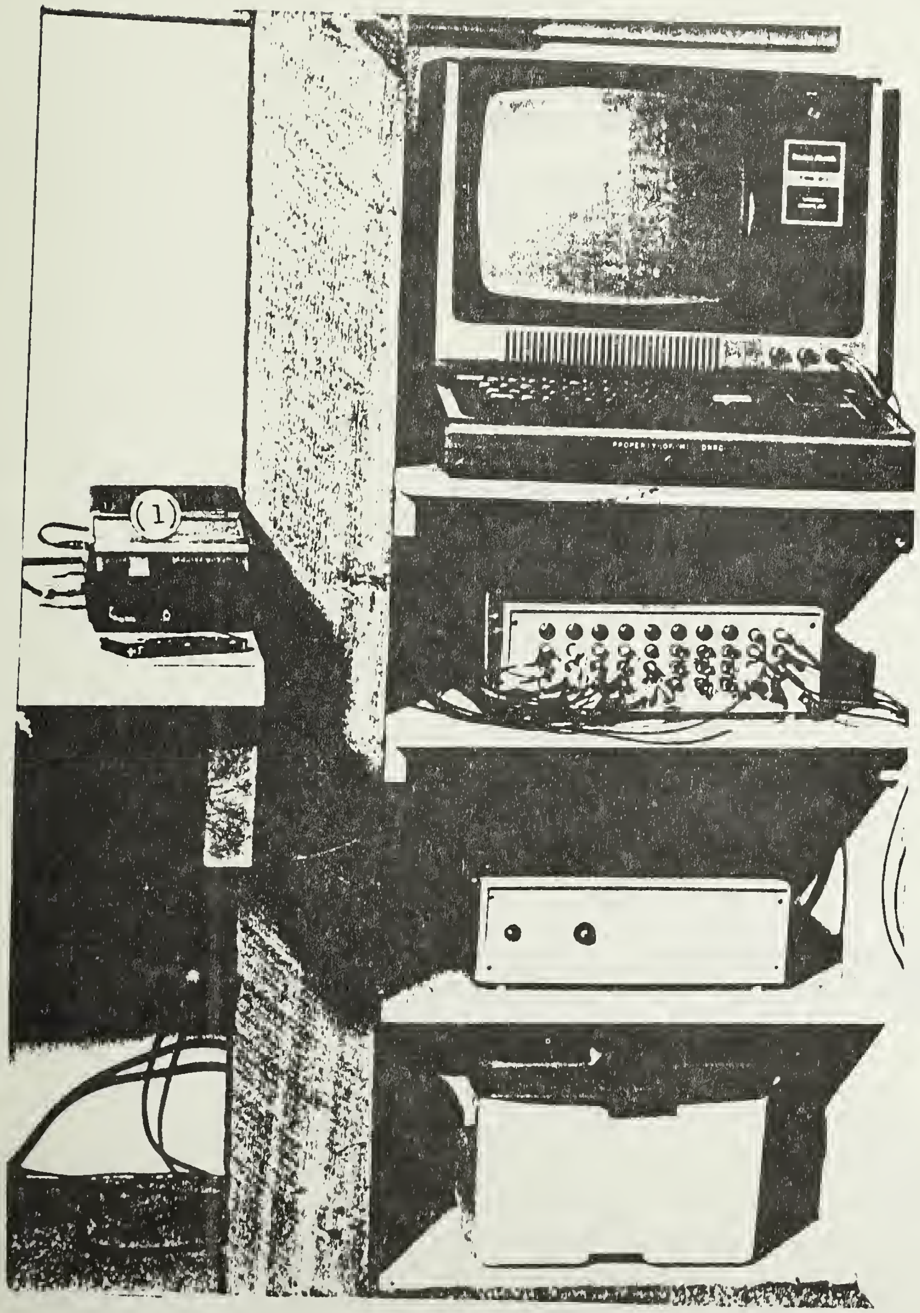


Figure 1: Computer-Based Data Acquisition System

THERMAL PERFORMANCE

OF THE OIEN SOLAR HOUSE

by

Charless W. Fowlkes

FOWLKES ENGINEERING
31 Gardner Park Drive
Bozeman, MT 59715

for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM

Grant #RAE-145-800

NOTE ON UNITS

The test results in this report are given in metric or SI units. This convention corresponds to current professional practice and is in accord with the recommendations of the International Solar Energy Society and most technical journals.

Most readers are familiar with the Celsius or Centigrade temperature scale (^{o}C) and with power measured in kilowatts (kW). The metric unit of energy is the Joule (J). Most energy quantities in this report are expressed in megajoules (MJ) which is 10^6 joules or a million joules (1,000 BTU = 1 kBTU = 1.05 MJ). Since one MJ is about one thousand BTU's, a furnace with a rating of 100 thousand BTU/hour would be rated at about 100 MJ/hour. This approximate conversion will be useful to the reader accustomed to thinking in thousands of BTU.

Other abbreviations included in this report are: l = liters, m = meters, m^2 = square meters and kWh = kilowatt hours.

ABSTRACT

This residence is owned by Orville Oien and is located about seven miles west of Conrad, Montana. The house was retrofit with 8.2 m^2 (89 ft^2) of liquid solar collectors mounted on the roof which utilize adjustable reflectors. Heat is stored in water tanks located in the basement and having a total volume of 6410 l (1700 gal). Heat is transmitted from the storage to the living space by natural conduction and convection. Auxiliary heat is provided by a forced air furnace burning fuel oil.

This system was monitored during March, April and May of 1980. During the monitoring period the solar collectors provided 25% of the heat requirements of the house. The average daily collector efficiency during the entire monitoring period was 41%. The thermal performance of these home-built collectors was comparable to the performance of commercial collectors of similar design. The adjustable reflectors were not operating during the monitoring period, which reduced the amount of heat produced by the solar collectors.

SOLAR COLLECTOR

Type: Active liquid
Manufacturer: Home-made
Aperture Area: 8.2 m^2
Tilt: 75°
Azimuth: 0°
Glazing: Double glazed; glass
Absorber: Tube-in-plate Roll-Bond by Olin Brass
Fluid: 50/50 ethylene glycol/water
Thermal Capacity: 0.0034 MJl^{-1} $°C^{-1}$
Flow Rate: 15.8 l min^{-1}

STORAGE SYSTEM

Material: Water
Volume: 6.41 m^3
Thermal Mass: 26.6 MJ-$°C^{-1}$

AUXILIARY HEAT

Type: Forced Air
Fuel: Oil
Capacity: 120 $MJhr^{-1}$ (estimated)

BUILDING

Type: Wood frame, single story with basement
Floor Area: 148.4 m^2
Calc. Loss Factor: 0.81 $MJhr^{-1}$ $°C^{-1}$
Measured Loss Factor: 0.6 $MJhr^{-1}$ $°C^{-1}$

TABLE OF CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION

The Oien residence is located about seven miles west of Conrad, Montana. The solar system was designed and built by Orville and David Oien and consists of active liquid collectors incorporating adjustable reflectors.

2.0 DESCRIPTION OF THE HOUSE

Photographs of the exterior of the Oien house are shown in Figure 1. The solar collectors are tilted at approximately 75^{o} and face due south. The aluminum panels below the solar collectors are adjustable and they are intended to reflect solar radiation onto the collector panels. Above the collectors is an overhang whose lower surface is also reflective. The photo in Figure 2 shows a close-up of the solar collectors. There is no significant shading of the collectors due to trees or buildings.

Figure 3 shows a floor plan of the house and Figure 4 shows a schematic cross-section of the house, which includes the solar system. The location of monitoring instrumentation is also shown in Figure 4.

The calculated heat load of the Oien house is shown in Table 1. The original or old house consisted of a single story frame dwelling built over a basement. A family room and entry was added to the house at a later date (see Figure 3). The old and new portions of the house are listed separately in the heat load calculations in Table 1. The insulation of the older part of the house has been upgraded, bringing the ceiling to R41. The concrete walls of the basement have been insulated with two inches of foam placed on the outside of the wall and extending beneath the ground. The overall calculated heat loss coefficient for the house is 0.81 $MJhr^{-1}\ {}^{o}C^{-1}$ or 429 $BTUhr^{-1}\ {}^{o}F^{-1}$.

3.0 TRANSDUCER ARRANGEMENT

A schematic of the transducer arrangement is shown in Figure 4 and a transducer log is reproduced in Figure 5. Solar radiation was measured in two places. One transducer was mounted in the plane of the collector and attached to the surface of the collector. This transducer is exposed to the same radiation as the collector surface, including reflected radiation and shading effects. A second solar radiation transducer was located outside of the hood and parallel to the plane of the collectors. These two measurements

allow an evaluation of the effectiveness of the concentrating reflectors.

The fluid in the collector loop is a 50/50 ethylene glycol/water mixture. A flow meter was installed in the collector line, Figure 2, and a status relay was connected to the collector pump, Figure 4. The average flow rate in the collector loop was 15.8 l min^{-1}, which is more than ample for the collector area.

The collector fluid circulated through heat exchangers located in 12 heat storage tanks filled with water. Temperature probes on the inlet and outlet pipes of the collector allowed the data acquisition system to calculate collector heat output any time the circulation pump was on. Twelve temperature probes were taped against the outside surfaces of the 12 heat storage tanks, using silicone heat transfer paste and an insulating pad. The domestic hot water preheat tank was instrumented with one surface temperature probe taped to the tank and insulated. The inlet and outlet temperatures of this tank were also monitored.

The air flow in the auxiliary furnace was mapped with a hot wire anemometer. The velocity of the air at several stations on the cross-section of the duct is shown in Figure 6. The inlet and outlet temperatures of the auxiliary furnace were each monitored with a rake of three probes which averaged the air temperature at the cross-section. A status relay was connected to the fan motor of the auxiliary furnace. These measurements allowed the data acquisition system to compute the heat output of the furnace during any five-second interval when the fan was on.

The air temperature inside the house was measured at two locations. One probe was located in the living room in the old house and another probe in the family room. The ambient air temperature was measured with a probe located in a shaded area on the north side of the house.

The data acquisition system is described in Appendix II.

4.0 DATA ANALYSIS AND RESULTS

The accuracy of the data was assessed by performing a heat balance on the hourly data, the daily data and the monthly data. The basic heat balance equation is shown below:

$$\text{Input heat} - \text{Stored heat} = \text{Output heat}$$

The inputs consisted of solar heat delivered by the collectors, auxiliary heat delivered by the furnace and electric heat dissipated by lights and appliances. The heat output depends upon a heat loss factor multiplied by the measured temperature difference between the house and the outside ambient air. All the terms in the heat balance equation were measured on-line as true hourly averages with the exception of the electrical dissipation, which was an hourly average based upon readings of the power meter.

4.1 Hourly Data

Table 2 shows an example of hourly data for a 24-hour period beginning at midnight. (The hourly data for the entire monitoring period is shown in Appendix I.) The first two columns show the total solar radiation striking the collector array and the resulting heat output of the collectors. The last four columns of the table show the average collector inlet and outlet temperatures, the status of the circulating pump and the calculated collector efficiency.

Note that the collector efficiency increases during this day, reaching a maximum at 15:00 hours or at 3:00 p.m. This trend is due to the ambient temperatures, which are higher in the afternoon, and due to heat stored in the collector assembly. At 3:00 p.m., the solar radiation is decreasing and the collectors are delivering some heat that was stored during the previous hour.

Note in Table 2 that the solar radiation was nearly constant from 12:00 until 2:00 p.m. During this time, the collector efficiency was also constant at about 61%. Several test periods were selected when the solar radiation was constant and these values were used to construct collector efficiency curves. A collector efficiency curve for the Oien collector array is shown in Figure 7. The reference line in this figure shows the expected efficiency of a manufactured collector of this design. It can be seen that the experimental points follow the expected trend, but are about 10% below the reference curve.

Looking again at Table 2, the third column shows the hourly average heat delivered by the storage system. In the fourth column, SOLAR INPUT is calculated by adding COLLECTOR OUTPUT to STORAGE DELTA. The values of

STORAGE DELTA tend to be a little unstable because a large mass is multiplied by a very small, measured temperature difference. Allowing for these fluctuations, a comparison of the SOLAR INPUT and FURNACE OUTPUT depicts solar heat being added to the house. Column number six, SUM INPUT, is the sum of solar input, furnace output and average electrical dissipation. These can be compared to the next column, HEAT LOAD, which is calculated from a load factor multiplied by house temperature minus ambient temperature, the next two columns. The bottom line of Table 2 shows the 24-hour totals of all energy quantities and the 24-hour averages of all temperatures.

4.2 Daily Total Data

Table 3 summarizes the 24-hour totals and averages for each day during the entire monitoring period. This summary also includes the daily total insolation on the collector, labeled HOODED INSO, and the daily total radiation outside of the reflector, labeled OUTSIDE INSO. (The photograph in Figure 2 shows the mounting of these two transducers.) During March, there is little difference in the daily total insolation between the hooded and outside transducer. In May, the hooded insolation is reduced due to shading. It appears that the overhang reduces the diffuse insolation reaching the collector. During the test period, the reflectors were not properly adjusted to increase the reflected beam radiation.

4.3 Overall Summary

Table 4 summarizes the monthly totals of the major energy inputs and average temperatures. These numbers are combined to give the average performance throughout the total monitoring period. These data show that 25% of the heat requirements of this house were provided by the solar system. During the monitoring period, the solar collectors delivered 41% of the solar radiation as useful heat to the house. If the electric power used to drive the circulating pump is deducted, the net average collector efficiency becomes 39.5%. The solar heat delivered divided by the pump power consumed gives a coefficient of performance of 22. The solar collectors maintain the storage at 22.1°C, allowing heat to be

passively delivered to the living space, whose average temperature was 19.5°C. Table 5 summarizes monthly utility records of electric power. Table 6 shows long-term average degree-day data compared with specific monthly degree-day data during 1978 and 1979.

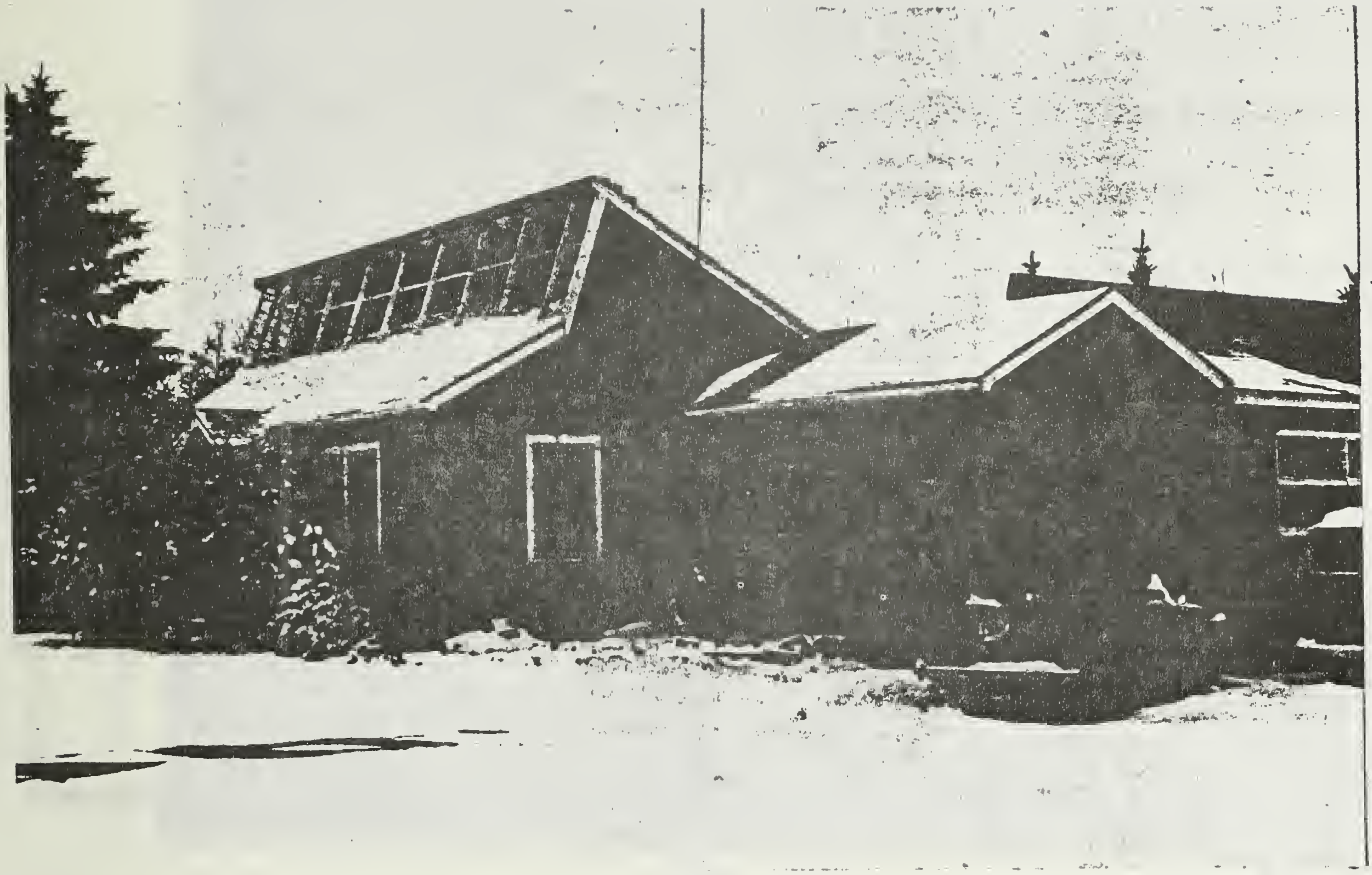
4.4 Graphical Presentation of Data

Figure 8 shows a graphical presentation of the hourly data for five cold days in March. The house temperature was a comfortable 20°C and did not fluctuate more than a few degrees during this period. The solar collector pump operated every day during this period. The solar radiation was more intense for the three days in the middle of this period, and the corresponding response of the storage temperature is evident. The ambient solar radiation and the solar radiation on the collector under the hood are very similar.

Figure 9 shows a graph covering five days in April. The solar radiation on the collector is much less than the ambient solar radiation, due to shading. There are larger swings in the house temperature during these five days. Inspection of the hourly data shows that the furnace was not being operated, which contributes to the temperature swing.

5.0 COMPARISON TO COMPUTER PREDICTION

Table 7 contains computer output from a simplified f-chart design procedure for the Oien system. This design routine uses solar radiation data and average weather from Choteau, Montana. This environmental data should be very similar to the conditions at Conrad. The computer simulation assumes that the solar system is a typical liquid collector system with storage and does not take into account the reflectors surrounding the solar collector or the passive heat distribution system. For the months of March through May, the computer simulation predicts a solar contribution of 23% of the heat load of the house. The monitoring results for the period beginning in March and ending in May showed the solar contribution as 25% of the heat load. The predicted average performance agrees with the measured performance within the monitoring period.



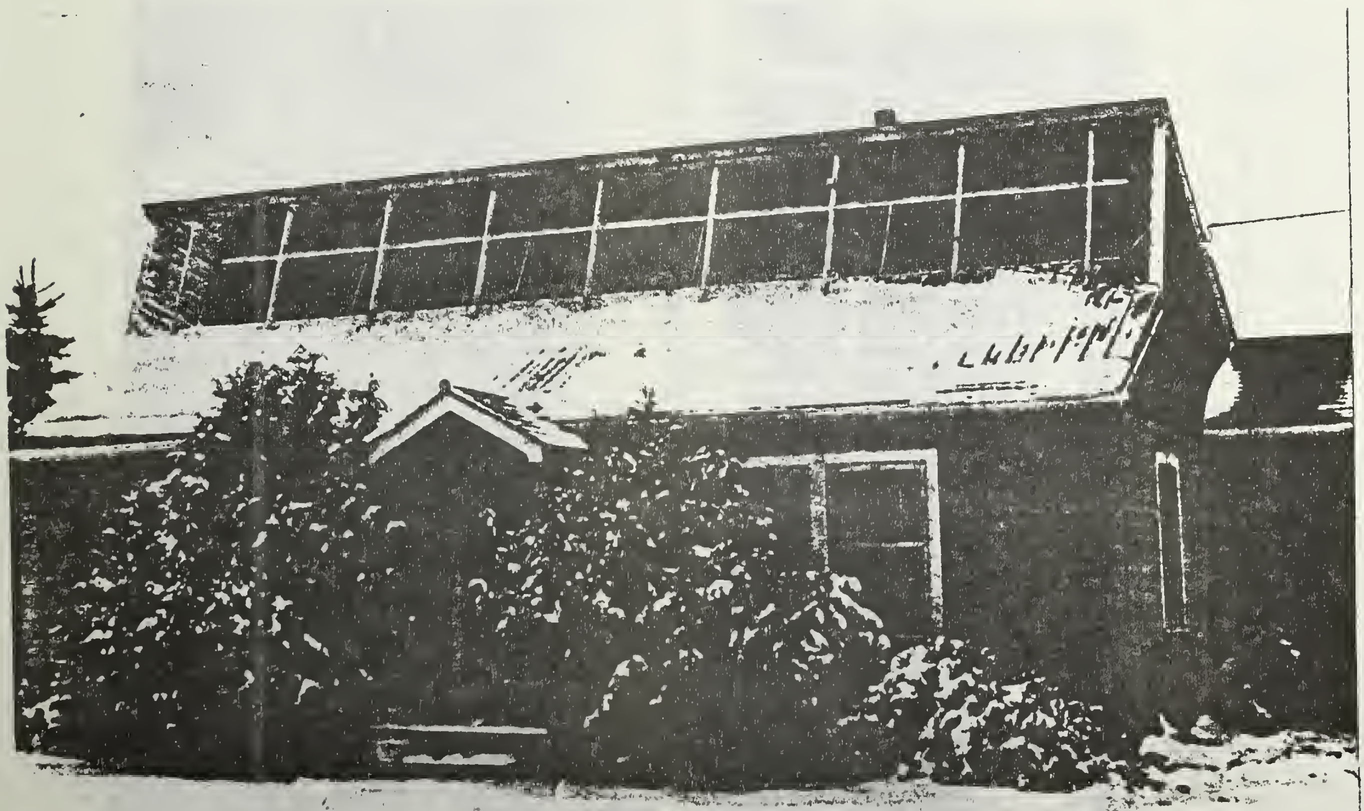
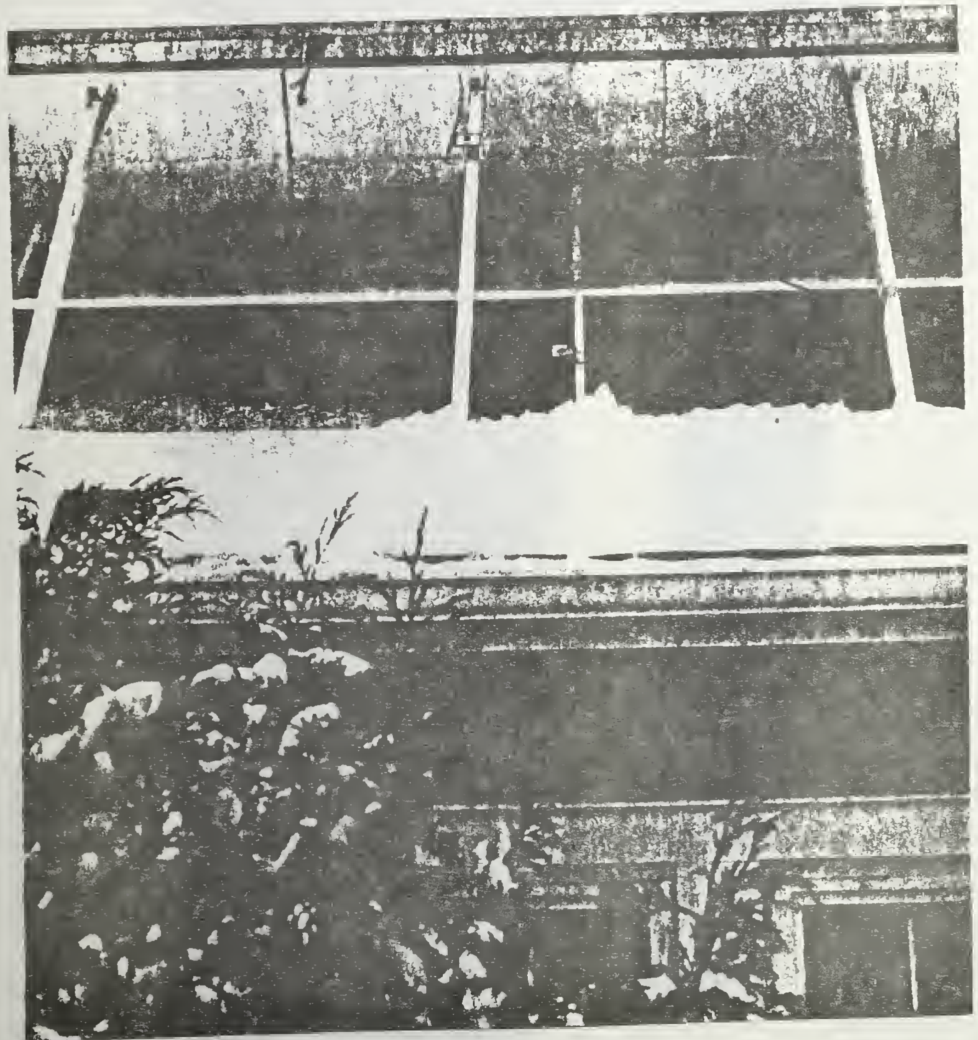
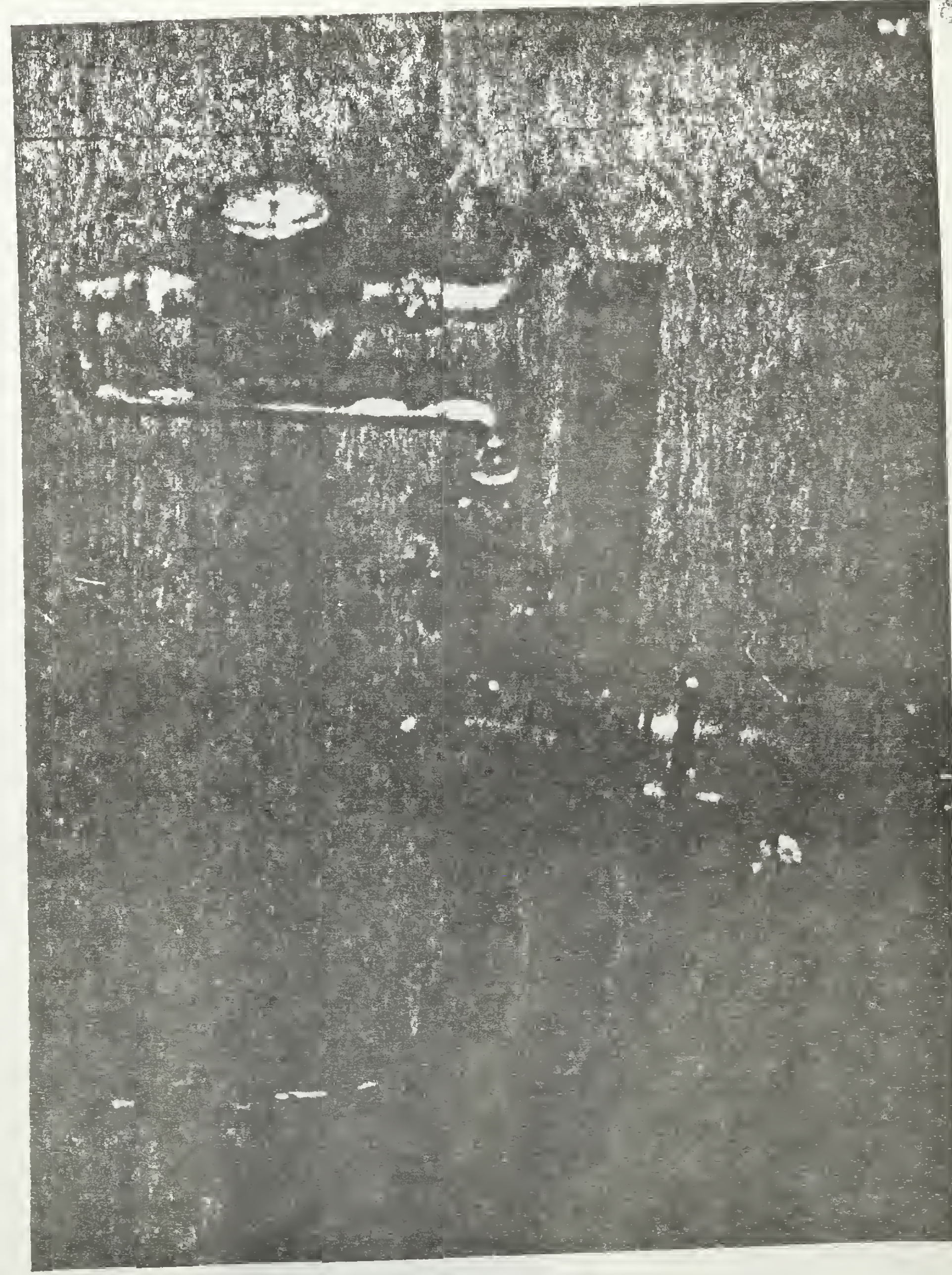


Figure 1: Photographs of the Oicn house and solar collectors.

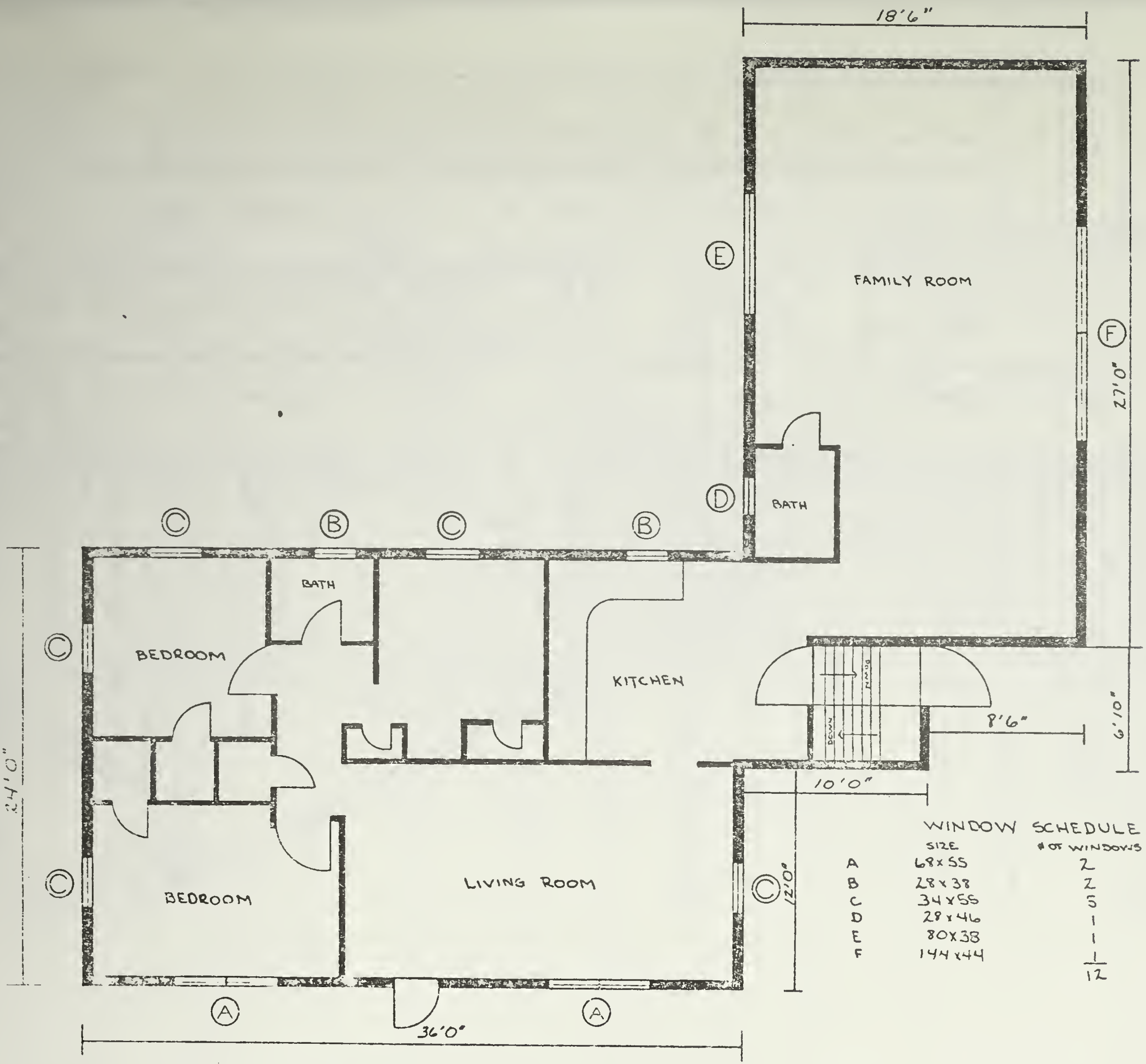


(a) Solar collectors and hood.



(b) Circulating pump and flow meter.

Figure 2: Oien solar house.



WINDOW SCHEDULE

	SIZE	# OF WINDOWS	SQ. FT.
A	68 x 55	2	51.9
B	28 x 38	2	14.7
C	34 x 55	5	64.9
D	28 x 46	1	3.9
E	80 x 38	1	21.1
F	144 x 44	1	44
		12	205.5

ure 3: Floor plan of Oien house.

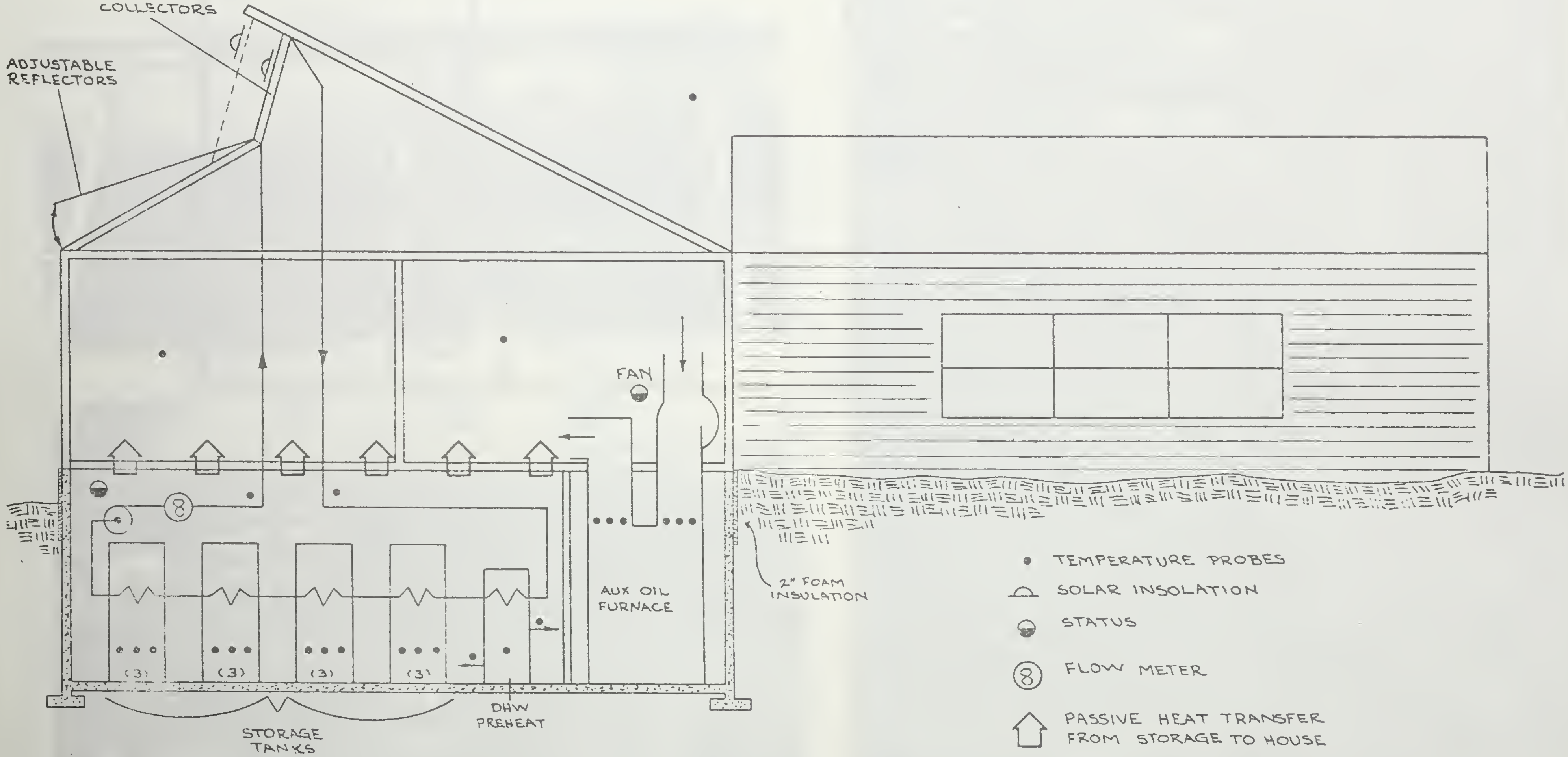


Figure 4: Cross-section of Oien house showing solar system and transducer layout.

TYPES:

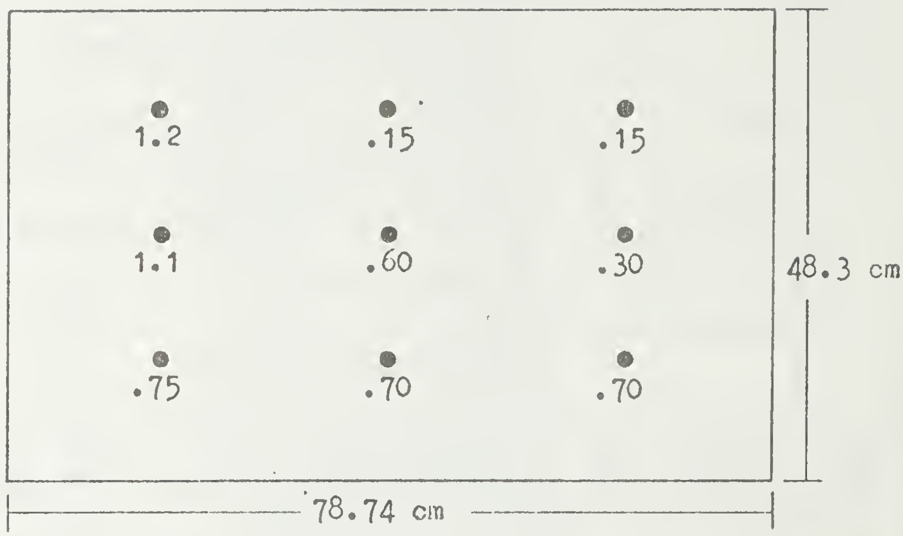
S - SOLAR
T - TEMP
DT - DUCT TEMP
ST - STATUS
P - POWER

Figure 5: TRANSDUCER LOG

OIEN HOUSE

DISK #	RS #	PROBE #	TYPE	LOCATION AND MOUNTING
1	1	2	S	Solar Transducer: Located on surface of collectors behind Reflective Hood
2	5	5	S	Solar Transducer: Located in front of Reflective Hood
3	6	relay	ST	Furnace Fan Status: Relay in parallel with Furnace Fan
4	7	relay	ST	Collector Pump Status: Relay in paralell with Furnace Fan
5	21		C	Collector Output
6	22		C	Collector Efficiency
7	25	22, 23, 24	DT	Furnace Inlet: Averaging set in Furnace hot air duct
8	26	55, 56, 57	DT	Furnace Outlet: Averaging set in Furnace hot air duct
9	27		C	Furnace Output
10	29	2, 7, 51	T	Water Storage Barrels
11	30	22, 23, 24	T	Water Storage Barrels
12	31	26, 27, 28	T	Water Storage Barrels
13	32	30, 32, 33	T	Water Storage Barrels
14	33	40	T	Collector Inlet
15	34	41	T	Cold Domestic Hot Water
16	35	42	T	Domestic Hot Water Tank Temperature
17	36	43	T	Preheated Water Outlet
18	37	44	T	Collector Outlet
19	3[illegible], 39	4[illegible], 49	[illegible]	[illegible] Temperatures: Averaged on disk
20	40	50	T	Ambient Temperature: Located on north side of house

FURNACE OUTLET

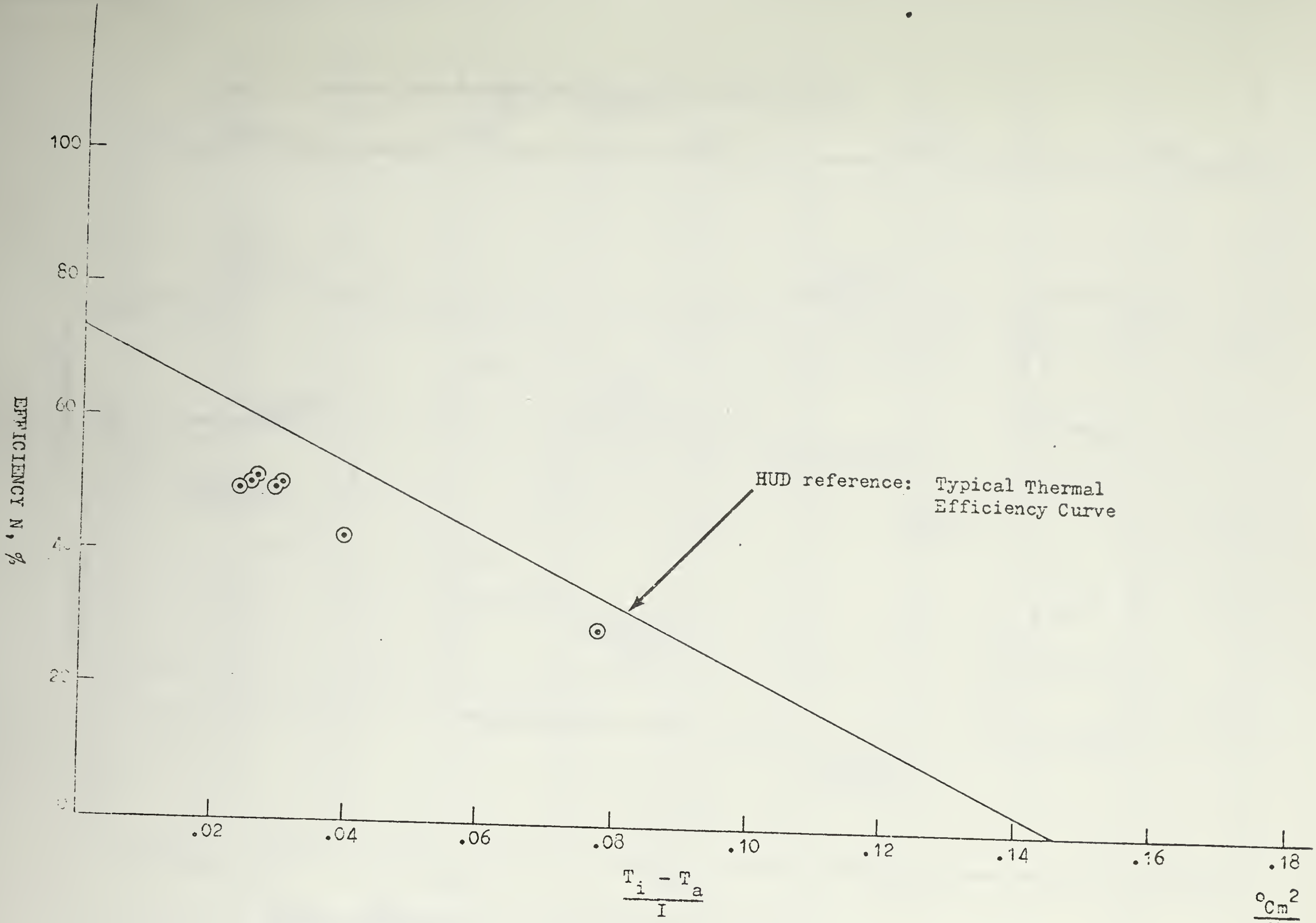


Area = $.38 m^2$

Average Velocity = .627m/sec.

Volume Flow Rate = $14.31 m^3/min.$

Figure 6: Air velocity in furnace outlet duct.



ure 7: Oien collector efficiency compared to HUD reference.

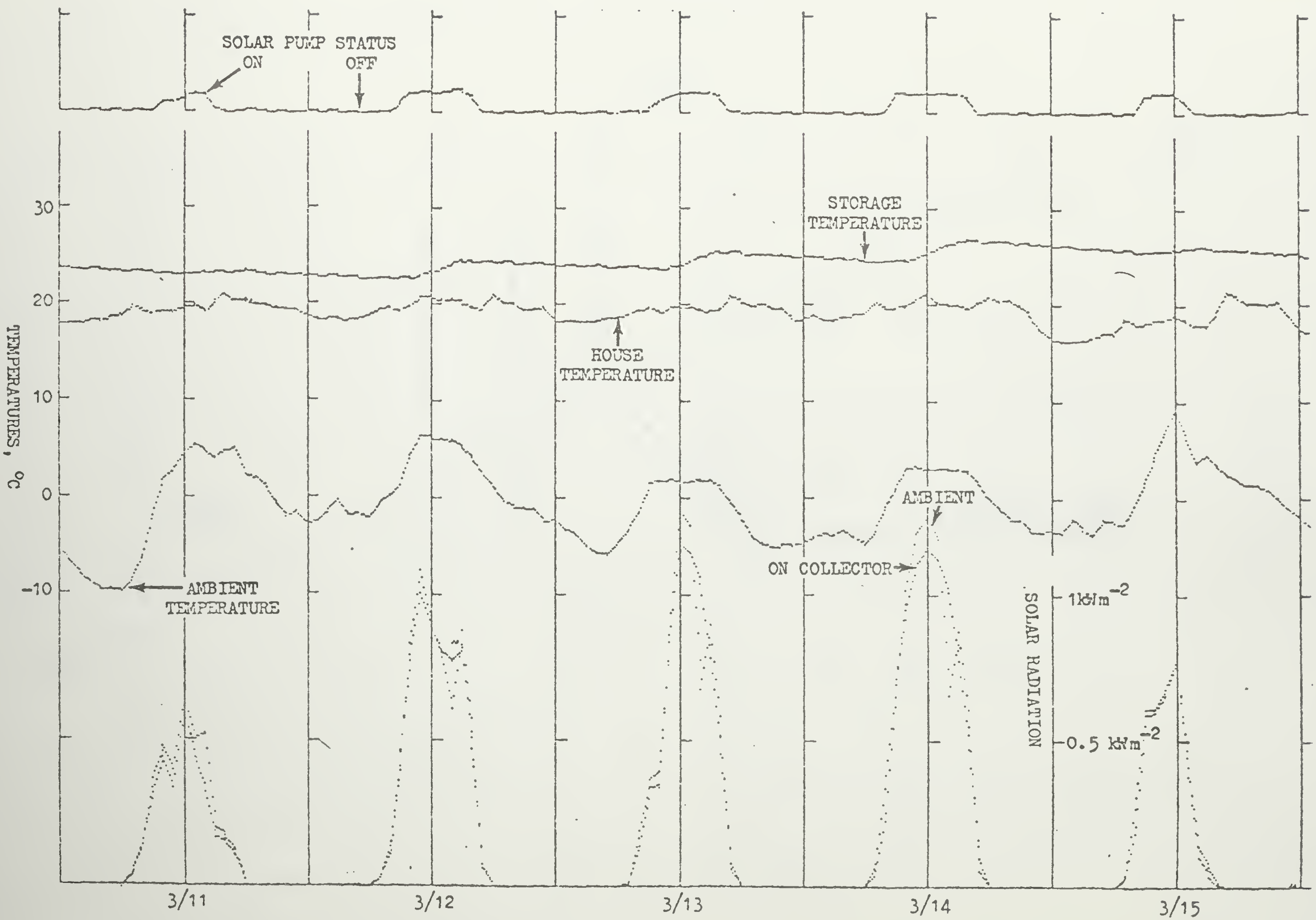


Figure 8: Graphical representation of data during five days in March.

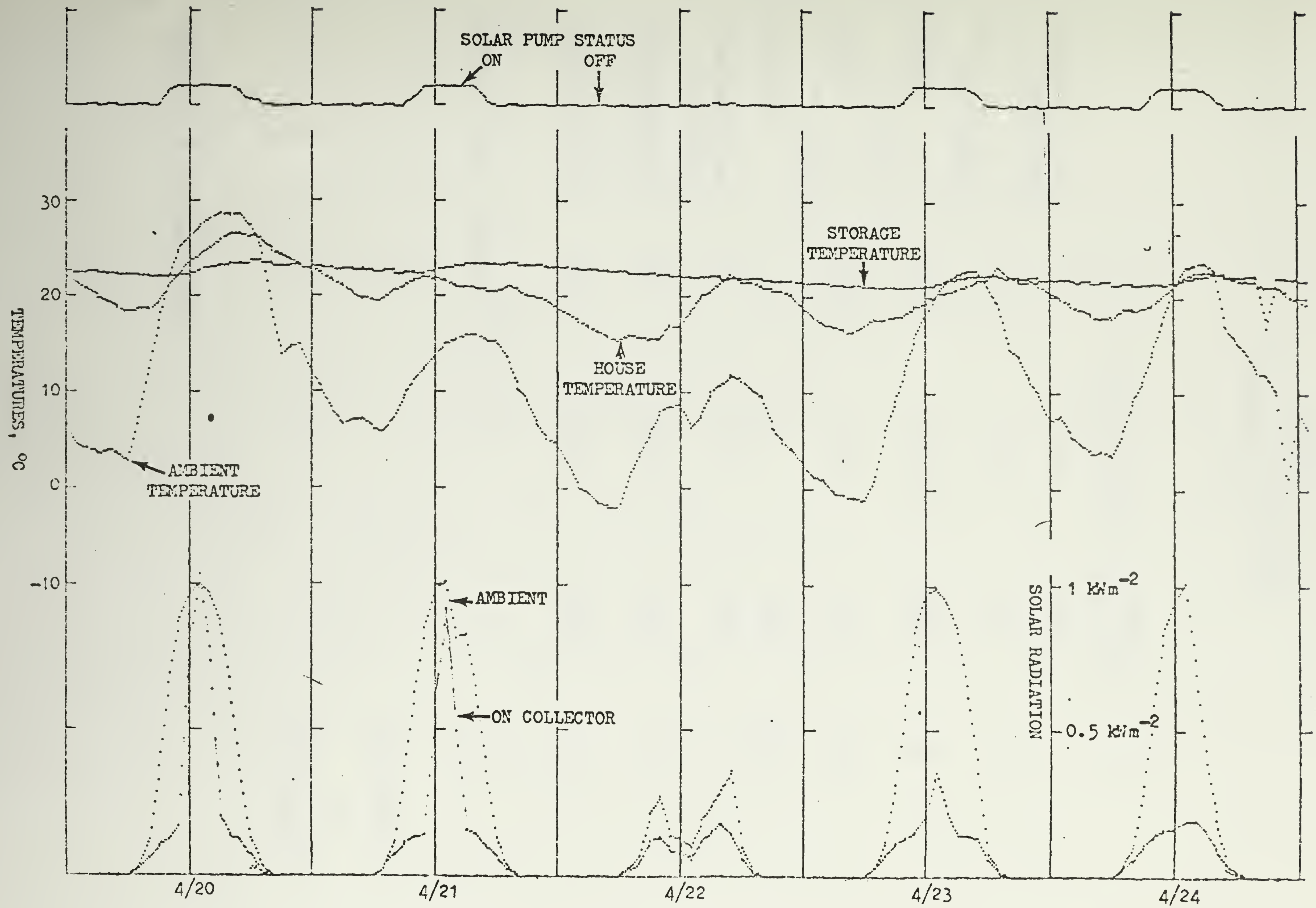


Figure 9: Graphical representation of data during five days in April.

TABLE 1

OIHN HOUSE HEAT LOAD

	R	U (Btu/hr ft^2 ^oF)	Area (sq. ft.)	U X A
Ceiling & Roof (old house)	41.3	.024	932	23
Ceiling & Roof (new house)	28.8	.035	655	23
Walls (old house)	15.9	.063	770	48
Walls (new house)	9.7	.013	612	63
Windows	1.7	.58	205	119
Basement Floor (old house)	80	.012	864	11
Basement Walls (old house)	60	.016	960	16
Addition Floor	60	.016	665	11
*Infiltration: 12780 ft^3 X $\frac{1}{2}$ X .018				115
				429 Btu/hr ^oF or 0.81 MJ/hr ^oC

*Assuming $\frac{1}{2}$ air change/hour

TABLE 2

SAMPLE HOURLY PERFORMANCE FOR ONE DAY

DAILY PERFORMANCE SUMMARY FOR THE OIEN PROJECT 3/ 1/80 R= 10

HR	SOLAR INSO (MJ)	COLL OUTPUT (MJ)	STORE DELTA (MJ)	SOLAR INPUT (MJ)	FURN OUTPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	STORE TEMP (C)	COLD TDHW (C)	DHW TANK (C)	DHW OUTLET (C)	COLL INLET (C)	COLL OUTLET (C)	COLL STAT (HRS)	COLL EFF (%)
0	.0	.0	1.9	1.9	12.5	18.3	20.4	20.7	-13.4	22.4	19.7	19.9	21.2	15.7	17.9	.0	.00
1	.0	.0	.9	.9	13.7	18.6	20.2	20.4	-13.3	22.3	19.6	19.8	21.1	15.7	17.7	.0	.00
2	.0	.0	1.1	1.1	18.0	23.1	21.3	20.2	-15.3	22.3	19.9	19.8	21.6	15.7	17.6	.0	.00
3	.0	.0	1.6	1.6	19.9	25.5	21.1	19.4	-15.7	22.2	19.9	19.8	21.4	15.7	17.5	.0	.00
4	.0	.0	1.2	1.2	19.6	24.8	20.3	19.4	-14.4	22.2	19.9	19.7	21.4	15.7	17.3	.0	.00
5	.0	.0	1.1	1.1	20.8	25.9	19.7	19.3	-13.5	22.2	20.0	19.7	21.5	15.7	17.2	.0	.00
6	.0	.0	1.5	1.5	22.7	28.1	19.3	19.4	-12.7	22.1	20.0	19.7	21.6	15.7	17.1	.0	.00
7	.0	.0	1.1	1.1	19.7	24.8	19.5	19.3	-13.1	22.1	20.0	19.6	21.5	15.7	17.1	.0	.00
8	1.2	.0	1.3	1.3	21.1	26.4	20.4	19.7	-14.2	22.0	20.0	19.6	21.5	15.8	17.0	.0	.00
9	6.2	-.0	.6	.6	1.5	6.1	18.9	18.8	-12.6	22.0	19.7	19.6	20.8	15.8	16.7	.0	-.00
10	19.0	7.5	.6	8.1	2.5	14.7	17.4	18.6	-10.4	22.0	19.1	19.7	20.2	24.0	27.1	.8	.42
11	28.6	14.4	-.1	14.3	1.5	19.8	16.3	19.1	-8.0	22.0	18.9	20.2	20.0	29.6	33.3	1.0	.54
12	35.6	19.4	-6.4	13.0	.0	17.0	15.4	19.5	-6.2	22.2	18.9	20.8	20.0	33.4	38.3	1.0	.58
13	37.8	21.7	-17.2	4.5	.0	8.5	14.6	19.7	-4.5	22.8	18.9	21.6	20.1	35.3	40.8	1.0	.61
14	37.0	21.5	-18.7	2.8	.0	6.8	13.5	19.6	-2.9	23.5	19.0	22.3	20.2	35.7	41.2	1.0	.62
15	26.9	18.8	-15.8	3.0	.0	7.0	12.7	19.3	-1.9	24.1	19.1	22.8	20.3	34.6	39.4	1.0	.75
16	25.4	14.1	-12.8	1.3	.0	5.3	12.1	19.0	-1.1	24.5	19.2	23.2	20.4	32.4	35.9	1.0	.57
17	15.4	5.9	-7.2	-1.3	.0	2.7	12.1	18.6	-1.6	24.8	19.2	23.4	20.4	28.3	30.2	.8	.41
18	2.5	.0	.1	.1	1.8	5.9	13.9	19.9	-3.3	24.8	19.1	23.3	20.2	22.0	25.7	.0	.00
19	.0	.0	.6	.6	15.4	20.0	16.9	21.6	-6.5	24.8	19.7	23.2	21.1	18.0	22.3	.0	.00
20	.0	.0	1.0	1.0	4.6	9.6	17.9	20.5	-9.4	24.7	19.5	23.0	20.2	16.7	20.7	.0	.00
21	.0	.0	1.1	1.1	8.4	13.5	17.9	20.2	-9.7	24.7	19.5	23.0	20.2	16.1	19.9	.0	.00
22	.0	.0	1.1	1.1	8.5	13.6	18.3	20.8	-9.7	24.6	19.6	22.9	20.3	15.8	19.5	.0	.00
23	.0	.0	1.3	1.3	3.8	9.1	17.7	20.3	-9.2	24.6	19.5	22.8	20.1	15.7	19.3	.0	.00
0	.0	.0	1.2	1.2	8.3	13.5	16.0	18.6	-8.1	24.5	19.3	22.7	19.8	15.6	18.9	.0	.00
	235.6	123.2	-58.8	64.4	224.1	388.5	433.4	19.7	-9.2	23.2	19.5	21.3	20.7	21.2	24.2	7.6	

TABLE 3

DAILY PERFORMANCE SUMMARY

MARCH

DAILY PERFORMANCE SUMMARY FOR THE OIEN PROJECT

DA	SOLAR INSO (MJ)	COLL OUTPUT (MJ)	STORE DELTA (MJ)	SOLAR INPUT (MJ)	FURN OUTPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBI TEMP (C)	STORE TEMP (C)	COLD TOWN (C)	DHW TANK (C)	DHW OUTLET (C)	HOOBED INSO MJ/M2	OTSIDE INSO MJ/M2	COLL STAT (HRS)	AUX POWER (MJ)
1	235.6	123.2	-53.8	64.4	224.1	333.5	433.4	19.7	-9.2	23.2	19.5	21.3	20.7	27.4	23.0	7.6	3.4
2	149.2	75.2	-19.1	56.1	183.5	335.6	327.0	19.5	-3.4	24.8	19.6	22.9	20.0	17.9	18.5	5.9	2.6
3	36.0	2.0	36.4	38.5	394.8	529.3	476.2	19.7	-14.7	24.6	20.1	22.0	20.3	7.2	1.6	.2	.1
4	44.9	3.1	40.4	43.6	425.6	565.1	572.0	20.0	-19.7	23.2	19.7	21.0	19.8	9.1	1.9	.2	.1
5	129.0	55.3	-.4	54.9	365.8	516.7	332.6	19.2	-21.3	22.3	20.0	21.0	20.2	18.0	13.5	5.6	2.5
6	192.8	83.0	-33.2	54.8	242.4	393.2	473.7	19.3	-13.6	23.0	19.1	22.0	19.2	23.5	23.5	7.8	3.5
7	164.7	76.8	-19.8	57.0	264.5	417.5	393.3	19.5	-3.8	23.9	19.5	22.9	19.7	20.1	20.1	5.8	2.6
8	159.9	72.6	-12.8	59.8	202.4	358.3	318.8	19.8	-2.4	24.4	19.9	23.4	20.0	19.1	19.9	5.1	2.3
9	69.1	14.7	33.9	48.5	157.8	302.3	274.2	19.8	.8	24.2	19.6	23.1	19.6	7.7	9.2	1.6	.7
10	97.0	32.1	19.6	51.7	128.8	270.5	300.8	19.2	-1.7	23.2	18.9	22.4	18.9	10.9	12.8	3.7	1.7
11	184.2	87.1	-33.6	55.5	95.1	246.6	266.1	19.5	1.0	23.4	19.0	22.7	19.1	22.5	22.5	7.2	3.2
12	183.6	86.9	-25.3	61.5	127.0	234.6	305.3	19.2	-2.0	24.4	19.3	23.5	19.5	22.8	23.2	6.3	2.8
13	231.3	106.9	-35.2	71.7	108.8	276.4	274.2	19.6	-.9	25.6	19.8	24.4	19.9	28.2	28.3	7.8	3.5
14	103.9	42.5	36.4	72.8	62.9	231.8	251.1	18.4	1.0	25.8	19.4	24.3	19.6	12.7	13.2	4.4	2.0
15	182.3	84.6	-8.6	76.0	60.6	232.7	237.3	18.7	-1.4	25.3	19.4	23.9	19.5	21.8	22.6	6.5	2.9
16	217.9	95.0	-16.3	78.8	53.4	228.2	277.1	18.5	-2.1	25.7	19.2	24.3	19.4	26.2	26.9	7.5	3.3
17	59.2	21.5	45.8	67.3	31.9	175.2	251.6	17.0	1.5	25.2	18.9	23.6	19.1	6.5	8.0	2.6	1.2
18	166.8	74.5	8.7	83.2	44.2	225.3	239.1	18.8	2.2	24.5	19.0	23.1	19.3	19.4	21.3	7.1	3.2
19	101.8	33.6	21.8	60.4	28.6	185.0	248.5	18.3	1.0	23.7	18.8	22.9	19.1	11.5	13.3	4.4	2.0
20	196.9	89.0	-21.4	67.6	30.2	193.8	242.6	18.2	1.4	23.7	18.5	23.0	18.7	23.5	24.5	7.1	3.2
21	40.3	.7	45.4	46.1	63.2	205.3	271.7	18.3	-.5	23.3	18.4	22.3	18.6	4.0	5.8	.0	.0
22	209.7	92.5	-14.3	78.2	84.2	258.4	257.8	19.5	1.6	22.7	18.8	21.9	19.0	25.3	25.9	7.4	3.3
23	121.5	42.5	15.1	57.5	12.6	166.1	248.6	17.2	1.7	22.7	18.3	20.4	18.6	14.0	15.6	4.4	2.0
24	58.3	7.4	34.8	42.3	41.0	179.3	273.7	18.4	-.6	21.8	17.9	21.5	18.1	6.3	7.9	.7	.3
25	125.5	46.0	.8	46.7	69.0	211.7	303.3	17.0	-2.1	21.2	17.9	21.1	18.0	14.5	16.1	4.9	2.2
26	172.8	72.0	-18.7	53.3	63.4	212.7	257.0	18.3	.5	21.5	17.9	21.6	18.0	20.6	21.6	6.7	3.0
27	100.2	35.5	14.4	50.0	8.3	134.2	227.8	17.7	1.9	21.6	17.4	21.7	17.7	11.3	13.1	4.3	1.9
28	214.2	87.6	-26.5	61.2	14.4	171.6	227.5	17.8	2.2	21.8	17.5	22.0	17.9	25.8	26.4	7.5	3.2
29	121.3	46.7	7.0	53.7	10.4	160.1	205.7	18.7	4.4	22.1	17.9	22.1	18.2	14.2	15.4	5.6	2.5
30	23.5	.0	35.2	35.2	93.3	224.4	235.2	18.5	-1.3	21.4	17.8	21.0	18.0	3.1	2.7	.0	.0
31	50.5	7.3	27.2	34.5	101.2	223.6	244.4	18.4	-.1	20.4	17.8	19.8	18.1	5.5	6.8	.6	.3

DAILY PERFORMANCE SUMMARY
APRIL

DAILY PERFORMANCE SUMMARY FOR THE OIEN PROJECT

DA	SOLAR INSO (MJ)	COLL OUTPUT (MJ)	STORE DELTA (MJ)	SOLAR INPUT (MJ)	FURN OUTPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	STORE TEMP (C)	COLD TDHW (C)	DHW TANK (C)	DHW OUTLET (C)	HOODED INSO MJ/M2	OTSIDE INSO MJ/M2	COLL STAT (HRS)	AUX POWER (MJ)
1	59.8	25.3	12.9	33.2	58.5	196.7	269.0	16.9	-1.0	19.5	16.7	19.7	16.8	10.5	4.0	3.7	1.7
2	58.9	25.3	5.6	30.9	97.3	226.2	249.5	16.6	-.7	19.2	16.7	19.5	16.8	10.0	4.3	4.4	2.0
3	167.7	69.0	-24.5	44.5	61.4	201.9	250.1	16.7	-.6	19.5	16.8	19.9	16.9	20.2	20.7	7.3	3.3
4	245.5	102.3	-41.6	60.7	69.8	225.5	267.2	17.5	-1.1	20.7	17.3	21.2	17.5	30.1	29.7	7.8	3.5
9	54.2	9.1	39.9	49.0	19.3	164.3	211.3	18.4	3.7	22.0	18.1	22.1	18.3	5.5	7.7	1.0	.5
10	35.5	2.6	35.6	33.2	24.7	158.9	235.5	19.0	2.7	20.5	17.5	20.7	17.8	3.5	5.4	.2	.1
11	169.1	67.7	-19.1	43.7	22.7	167.3	221.2	18.4	3.1	20.3	17.3	20.5	17.6	18.3	23.0	7.0	3.1
12	193.5	69.3	-17.7	51.7	16.8	164.4	202.4	18.2	4.2	21.0	17.6	21.2	17.8	21.1	24.8	6.9	3.1
13	167.5	69.1	-14.0	55.2	14.9	165.9	132.6	19.2	10.0	21.5	17.9	21.8	18.2	17.7	23.2	7.4	3.3
14	133.3	58.4	-4.8	53.6	.0	149.6	107.0	19.7	12.1	21.8	18.5	22.2	18.8	14.7	19.0	6.7	3.0
15	121.2	44.7	7.3	51.9	.0	147.9	151.3	19.2	8.7	21.8	18.5	22.2	18.7	10.5	19.1	5.8	2.6
16	170.9	69.6	-2.2	67.3	.0	163.3	144.4	19.5	9.5	21.7	18.3	22.3	18.6	17.0	24.7	7.3	3.3
17	163.2	71.5	-12.5	59.0	.0	155.0	87.6	20.3	14.2	22.0	18.7	22.8	19.0	16.5	23.3	7.4	3.3
18	166.1	70.0	-10.5	59.6	.0	155.6	112.6	21.6	13.8	22.4	19.4	23.2	19.7	15.2	25.3	7.2	3.2
19	103.3	50.4	3.1	53.5	.0	149.5	74.5	21.5	16.3	22.5	19.7	23.3	20.0	10.3	16.1	6.7	3.0
20	155.1	72.5	-13.2	59.3	.0	155.3	84.5	22.5	16.7	22.7	19.9	23.6	20.2	12.7	25.1	7.6	3.4
21	143.3	58.6	.8	59.5	.0	155.5	148.9	20.7	10.4	22.9	19.7	23.8	19.9	10.5	24.4	6.7	3.0
22	49.7	3.5	42.8	46.3	.0	142.3	137.3	18.5	5.3	22.1	18.6	22.9	18.9	4.4	7.8	.3	.1
23	124.7	62.0	-10.5	51.4	.0	147.4	119.9	19.5	11.2	21.5	18.4	22.2	18.6	6.3	24.2	6.9	3.1
24	96.5	50.3	-1.8	48.5	.0	144.5	118.4	20.4	12.1	21.6	18.9	22.4	19.2	4.9	13.8	5.9	2.6
25	121.0	63.2	-10.8	52.4	.0	148.4	109.3	20.7	13.1	22.0	19.1	22.6	19.3	4.6	24.9	7.0	3.1
26	120.6	58.1	-4.5	53.6	.0	149.6	118.2	20.3	12.1	22.3	19.1	23.0	19.4	4.3	25.1	6.7	3.0
27	120.3	60.1	-5.9	54.2	.0	150.2	105.3	21.1	13.8	22.5	19.4	23.3	19.7	4.4	24.9	6.9	3.1
28	112.2	56.6	-4.0	52.7	.0	148.7	92.2	22.3	15.9	22.6	19.8	23.5	20.0	5.5	21.9	7.1	3.2
29	110.6	53.3	-2.5	50.8	.0	146.8	101.5	22.2	15.1	22.8	20.2	23.6	20.4	5.7	21.3	6.9	3.1
30	63.5	21.1	22.3	43.5	10.6	146.1	140.0	20.0	9.9	22.4	19.1	23.1	19.3	5.1	11.6	3.0	1.3

MAY

DAILY PERFORMANCE SUMMARY FOR THE OIEN PROJECT

DA	SOLAR INSO (MJ)	COLL OUTPUT (MJ)	STORE DELTA (MJ)	SOLAR INPUT (MJ)	FURN OUTPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	STORE TEMP (C)	COLD TDHW (C)	DHW TANK (C)	DHW OUTLET (C)	HOODED INSO MJ/M2	OTSIDE INSO MJ/M2	COLL STAT (HRS)	AUX POWER (MJ)
1	117.3	54.9	-6.9	47.9	28.4	176.4	120.9	20.8	12.7	22.1	19.3	22.9	19.4	4.6	24.0	6.6	2.9
2	105.2	49.6	-2.8	46.8	.0	142.8	96.2	21.9	15.2	22.3	19.5	23.1	19.8	4.8	20.8	6.5	2.9
3	77.0	23.3	14.2	42.6	2.6	141.2	107.2	19.3	11.7	22.1	19.4	22.9	19.6	4.7	14.1	3.7	1.6
4	116.3	51.6	-7.0	44.6	13.3	153.8	94.2	20.4	13.9	22.0	19.3	22.8	19.5	4.3	24.1	6.5	2.9
5	116.8	53.4	-6.4	47.1	.0	143.1	93.4	22.3	15.4	22.2	19.7	23.1	19.9	4.5	24.0	6.6	3.0
6	118.2	48.4	12.4	60.7	.0	156.7	102.7	20.9	13.8	22.2	19.6	23.3	19.8	7.1	21.8	6.5	2.9
7	68.3	22.8	17.2	40.0	.0	136.0	116.9	18.7	10.6	21.6	19.1	23.0	19.4	6.0	10.6	3.2	1.5
8	101.5	43.5	-3.1	40.4	22.5	158.9	103.4	19.6	12.1	21.3	19.2	22.6	19.3	6.2	13.5	6.2	2.6
9	21.4	.0	23.4	23.4	.0	124.4	137.9	18.9	9.2	20.9	18.8	21.8	19.0	1.9	3.3	.0	.0
10	117.9	42.4	-3.9	[illegible]	17.5	142.2	144.1	18.5	9.3	20.5	18.5	21.2	18.6	5.7	[illegible]	5.5	2.5
11	[illegible]	43.4	-3.4	[illegible]	[illegible]	135.6	143.1	17.6	7.3	20.6	[illegible]	21.6	18.5	5.2	[illegible]	[illegible]	[illegible]
12	117.9	44.3	-2.1	42.1	.0	137.1	[illegible]	[illegible]	[illegible]	20.7	[illegible]	21.6	18.7	5.2	[illegible]	[illegible]	[illegible]
13	117.5	48.6	-5.4	43.2	.0	139.2	124.8	19.2	10.5	20.8	18.3	22.1	18.6	6.3	22.3	6.7	[illegible]
14	111.3	42.0	-.6	41.4	.0	137.4	125.4	19.5	10.8	20.9	18.5	22.2	18.7	4.8	22.4	5.9	2.6

TABLE 4

OVERALL PERFORMANCE SUMMARY OF OTEN SOLAR HOUSE

Month	Days	Solar Input MJ	Collector Output MJ	Pump Power MJ	Furnace Output MJ	Elect. Dissip. MJ	Total Input MJ	Calc. Heat Load MJ	House Temp. °C	Ambient Temp. °C	Storage Temp. °C
March	31	4149	1710	66	3792	2976	8478	9660	19.0	-2.7	23.4
April	26	3238	1362	68	398	2496	4256	4043	19.6	8.9	21.6
May	14	1419	573	34	80	1344	1997	1697	20.0	11.6	21.4
Total	71	8806	3645	168	4270	6816	14731	15400	19.5	5.9	22.1
Heat Distribution			25%		29%	46%	100%				

Average Collector Efficiency 41% Gross; 39.5% Net

Coefficient of Performance 22

TABLE 5

MONTHLY UTILITY RECORDS OF ELECTRIC POWER

	1978 kWh	1979 kWh	1980 kWh
January	1899	2370	1736
February	2472	1957	1605
March	2234	1410	1597
April	1262	1068	1142
May	928	935	1327
June	1020	714	1200
July	699	808	1048
August	848	1006	
September	968	1035	
October	880	958	
November	1058	1223	
December	1050	1298	

Note: Mr. Oien estimates that 500 kWh/month is used for running a pump to water cattle and to operate equipment in a workshop. The remaining energy is used in the house.

TABLE 6

CONRAD DEGREE DAY DATA

(Degrees Celsius)

Month	Long-Term Average	1978 Degree Days	1978 Ratio	1979 Degree Days	1979 Ratio
January	795	1017	1.27	1039	1.31
February	616	808	1.31	782	1.27
March	606	568	.94	529	.87
April	375	366	.98	421	1.12
May	217	253	1.16	251	1.16
June	112	78	.70	88	.78
July	32	50	1.56	39	1.21
August	47	75	1.59	17	.36
September	167	156	.93	103	.62
October	313	314	1.00	306	.98
November	538	718	1.33	560	1.04
December	704	855	1.21	591	.84
TOTAL	4522	4450	.98	4726	1.04

TABLE 7: PERFORMANCE PREDICTED BY F-CHART

MON	----DAILY---- SOLAR RAD KWH/m2	AMBT TEMP (C)	----MONTHLY---- DEGREE DAYS (C-DAY)	WATER LOAD KWH	HEAT LOAD KWH	TOTAL LOAD KWH	SOLAR FRAC (%)	SOLAR ENERGY KWH	BACKUP ENERGY KWH
JAN	3.2	-6.1	756	0	4083	4083	8	331	3752
FEB	3.2	-2.9	596	0	3216	3216	10	333	2883
MAR	4.3	-.8	594	0	3210	3210	16	501	2709
APR	4.6	5.7	378	0	2043	2043	26	536	1507
MAY	4.2	10.9	231	0	1245	1245	37	460	785
JUN	4.7	14.8	118	0	636	636	70	445	191
JUL	5.0	19.1	26	0	141	141	100	141	0
AUG	4.8	18.0	47	0	255	255	100	255	0
SEP	4.8	12.8	178	0	960	960	53	508	452
OCT	4.5	8.3	310	0	1674	1674	31	514	1160
NOV	3.2	1.0	520	0	2808	2808	12	337	2471
DEC	2.3	-3.1	665	0	3591	3591	5	195	3396
YEAR	4.1	6.5	4419	0	23862	23862	19	4556	19306

YEARLY SOLAR FRACTION.... .19

CLIENT................... OIEN
LOCATION................. CHOTEAU

COLLECTOR AREA........... 8.20 m2, 88.2 ft2
COLLECTOR TILT........... 60 DEGREES
COLLECTOR TYPE........... LIQUID
EFFICIENCY SLOPE......... 4.96 W/C-m2, .87 BTU/F-ft2
Y-INTERCEPT.............. .72
HOUSE LOAD FACTOR........ .23 KWH/C-HOUR, 426 BTU/F-HOUR

APPENDIX I

TABLES OF HOURLY PERFORMANCE DATA FOR OPEN HOUSE

EQUATIONS USED TO PROCESS DATA

```
500 REM *** CALCULATE HOURLY DATA ***
505 S(1)=(V(1)+V(2))/2*3.6*8.2\REM SOLAR INSOLATION
515 S(2)=V(5)\REM COLLECTOR OUTPUT
517 S(10)=(V(10)+V(11)+V(12)+V(13))/4\REM STORAGE TEMPERATURE
518 IF K4=0THEN F1=S(11)
519 S(3)=27.92*(F1-S(10))\REM STORAGE DELTA
520 S(4)=27.92*(F1-S(10))+S(2)\REM ESTIMATED SOLAR INPUT
522 F1=S(10)\REM PREVIOUS HOUR VALUE
525 S(5)=V(9)\REM FURNACE OUTPUT
527 IF V(8)>60 THEN S(5)=V(3)*29\REM SHORTED FURNACE OUTLET PROBE
530 S(6)=S(5)+S(4)+4\REM SUMM INPUT
535 S(7)=.6*(V(19)-V(20))\REM HEAT LOAD
540 S(8)=V(19)\REM HOUSE TEMPERATURE
545 S(9)=V(20)\REM AMBIENT TEMPERATURE
555 S(11)=V(15)\REM COLD DHW TEMPERATURE
560 S(12)=V(16)\REM DHW TANK TEMERATURE
565 S(13)=V(17)\REM DHW OUTLET TEMERATURE
570 S(14)=V(14)\REM COLLECTOR INLET TEMPERATURE
575 S(15)=V(18)\REM COLLECTOR OUTLET TEMPERATURE
580 S(16)=V(4)\REM COLLECTOR STATUS
585 S(17)=V(5)/((V(1)+V(2))/2+.0001)/27.6\REM COLLECTOR EFFICIENCY
```

TABLE 1

DAILY PERFORMANCE SUMMARY FOR THE OIEN PROJECT 2/ 29/80 R= 1

HR	SOLAR INSO (MJ)	COLL OUTPUT (MJ)	STORE DELTA (MJ)	SOLAR INPUT (MJ)	FURN OUTPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	STORE TEMP (C)	COLD TDHW (C)	DHW TANK (C)	DHW OUTLET (C)	COLL INLET (C)	COLL OUTLET (C)	COLL STAT (HRS)	COLL EFF (%)
15	6.9	.1	-630.4	-630.4	26.1	-600.3	16.3	21.8	-5.3	22.6	21.4	20.2	23.2	20.6	21.6	.0	.01
16	4.7	.0	-5.9	-5.9	4.9	3.1	16.4	21.6	-5.8	22.8	22.4	20.2	24.1	19.0	22.4	.0	.00
17	3.0	.1	.6	.7	16.5	21.2	17.5	22.6	-6.6	22.8	22.8	20.2	24.2	18.6	20.4	.0	.03
18	.7	.0	2.0	2.0	.0	6.0	16.6	20.2	-7.5	22.7	22.0	20.1	22.4	17.6	19.5	.0	.00
19	.0	.0	2.0	2.0	.0	6.0	17.8	21.0	-8.6	22.6	20.7	20.1	21.3	16.6	19.3	.0	.00
20	.0	.0	1.0	1.0	6.2	11.2	18.0	20.4	-9.7	22.6	20.0	20.1	21.1	16.1	18.9	.0	.00
21	.0	.0	1.7	1.7	10.1	15.8	19.3	20.3	-11.9	22.5	19.9	20.0	21.2	15.9	18.6	.0	.00
22	.0	.0	1.4	1.4	10.4	15.8	20.7	20.5	-13.9	22.5	19.8	20.0	21.2	15.8	18.4	.0	.00
23	.0	.0	1.0	1.0	13.6	18.6	20.9	20.4	-14.4	22.4	19.7	19.9	21.1	15.8	18.2	.0	.00
	15.4	.1	-626.5	-626.4	87.8	-502.6	163.5	21.0	-9.3	22.6	21.0	20.1	22.2	17.3	19.7	.0	

TABLE 2

DAILY PERFORMANCE SUMMARY FOR THE OIEN PROJECT 3/ 1/80 R= 10

HR	SOLAR INSO (MJ)	COLL OUTPUT (MJ)	STORE DELTA (MJ)	SOLAR INPUT (MJ)	FURN OUTPUT (MJ)	SUMM INPUT (MJ)	HEAT LOAD (MJ)	HOUSE TEMP (C)	AMBT TEMP (C)	STORE TEMP (C)	COLD TDHW (C)	DHW TANK (C)	DHW OUTLET (C)	COLL INLET (C)	COLL OUTLET (C)	COLL STAT (HRS)	COLL EFF (%)
0	.0	.0	1.9	1.9	12.5	18.3	20.4	20.7	-13.4	22.4	19.7	19.9	21.2	15.7	17.9	.0	.00
1	.0	.0	.9	.9	13.7	18.6	20.2	20.4	-13.3	22.3	19.6	19.8	21.1	15.7	17.7	.0	.00
2	.0	.0	1.1	1.1	18.0	23.1	21.3	20.2	-15.3	22.3	19.9	19.8	21.6	15.7	17.6	.0	.00
3	.0	.0	1.6	1.6	19.9	25.5	21.1	19.4	-15.7	22.2	19.9	19.8	21.4	15.7	17.5	.0	.00
4	.0	.0	1.2	1.2	19.6	24.8	20.3	19.4	-14.4	22.2	19.9	19.7	21.4	15.7	17.3	.0	.00
5	.0	.0	1.1	1.1	20.8	25.9	19.7	19.3	-13.5	22.2	20.0	19.7	21.5	15.7	17.2	.0	.00
6	.0	.0	1.5	1.5	22.7	28.1	19.3	19.4	-12.7	22.1	20.0	19.7	21.6	15.7	17.1	.0	.00
7	.0	.0	1.1	1.1	19.7	24.8	19.5	19.3	-13.1	22.1	20.0	19.6	21.5	15.7	17.1	.0	.00
8	1.2	.0	1.3	1.3	21.1	26.4	20.4	19.7	-14.2	22.0	20.0	19.6	21.5	15.8	17.0	.0	.00
9	6.2	-.0	.6	.6	1.5	6.1	18.9	18.8	-12.6	22.0	19.7	19.6	20.8	15.8	16.7	.0	-.00
10	19.0	7.5	.6	8.1	2.5	14.7	17.4	18.6	-10.4	22.0	19.1	19.7	20.2	24.0	27.1	.8	.42
11	28.6	14.4	-.1	14.3	1.5	19.8	16.3	19.1	-8.0	22.0	18.9	20.2	20.0	29.6	33.3	1.0	.54
12	35.6	19.4	-6.4	13.0	.0	17.0	15.4	19.5	-6.2	22.2	18.9	20.8	20.0	33.4	38.3	1.0	.58
13	37.8	21.7	-17.2	4.5	.0	8.5	14.6	19.7	-4.5	22.8	18.9	21.6	20.1	35.3	40.8	1.0	.61
14	37.0	21.5	-18.7	2.8	.0	6.8	13.5	19.6	-2.9	23.5	19.0	22.3	20.2	35.7	41.2	1.0	.62
15	26.9	18.8	-15.8	3.0	.0	7.0	12.7	19.3	-1.9	24.1	19.1	22.8	20.3	34.6	39.4	1.0	.75
16	25.4	14.1	-12.8	1.3	.0	5.3	12.1	19.0	-1.1	24.5	19.2	23.2	20.4	32.4	35.9	1.0	.59
17	15.4	5.9	-7.2	-1.3	.0	2.7	12.1	18.6	-1.6	24.8	19.2	23.4	20.4	28.3	30.2	.8	.41
18	2.5	.0	.1	.1	1.8	5.9	13.9	19.9	-3.3	24.8	19.1	23.3	20.2	22.0	25.7	.0	.00
19	.0	.0	.6	.6	15.4	20.0	16.9	21.6	-6.5	24.8	19.7	23.2	21.1	18.0	22.3	.0	.00
20	.0	.0	1.0	1.0	4.6	9.6	17.9	20.5	-9.4	24.7	19.5	23.0	20.2	16.7	20.7	.0	.00
21	.0	.0	1.1	1.1	8.4	13.5	17.9	20.2	-9.7	24.7	19.5	23.0	20.2	16.1	19.9	.0	.00
22	.0	.0	1.1	1.1	8.5	13.6	18.3	20.8	-9.7	24.6	19.6	22.9	20.3	15.8	19.5	.0	.00
23	.0	.0	1.3	1.3	3.8	9.1	17.7	20.3	-9.2	24.6	19.5	22.8	20.1	15.7	19.3	.0	.00
0	.0	.0	1.2	1.2	8.3	13.5	16.0	18.6	-8.1	24.5	19.3	22.7	19.8	15.6	18.9	.0	.00
	235.6	123.2	-58.8	64.4	224.1	388.5	433.4	19.7	-9.2	23.2	19.5	21.3	20.7	21.2	24.2	7.6	

APPENDIX II

DATA ACQUISITION SYSTEM

A low cost data acquisition system was developed for solar performance monitoring and is pictured in Figure 1 on the following page. The heart of the system is a Radio Shack TRS-80 computer having a 4K memory. This system has the capability of 40 input channels and is controlled by a Level II BASIC program which allows the user to structure data sampling and processing procedures. Calibration constants, error checks, scan rate, data averaging, printing, etc., can be manipulated using this program capability. A real time clock within the A/D converter chassis is used to time the data output on the cassette. Scanning at an average rate of 40 channels per five seconds, the data is averaged at the end of each hour. This data is then written onto the cassette recorder for processing at a later time.

Temperatures were measured using AD-590 transducers made by Analog Devices. A BASIC computer program was used with the data acquisition system to calibrate the probes against a precision thermometer. The absolute accuracy of the temperatures measured is better than 0.5°C (1°F), while the accuracy of small temperature differences is 0.1°C (0.18°F).

Total solar radiation on the collector surface was measured using a silicon cell pyranometer. The device was manufactured by the contractor and is mounted in the plane of the solar collector. The device has been referenced to NOAA Standards with an estimated overall accuracy of 5%.

Electric power is measured using clamp-on ammeters calibrated on-site against the utility kWh meter. The status of motors, dampers, curtains and fans is determined using appropriate relays, microswitches or mercury switches.

Flow in liquid systems is measured using Hersey MVR-30 turbine meters which have been interfaced to the DAS. Flow in air systems is mapped using a hot-wire anemometer for a one-time measurement to characterize the flow. Status switches and software combine the one-time measurements to calculate appropriate heat flow quantities.

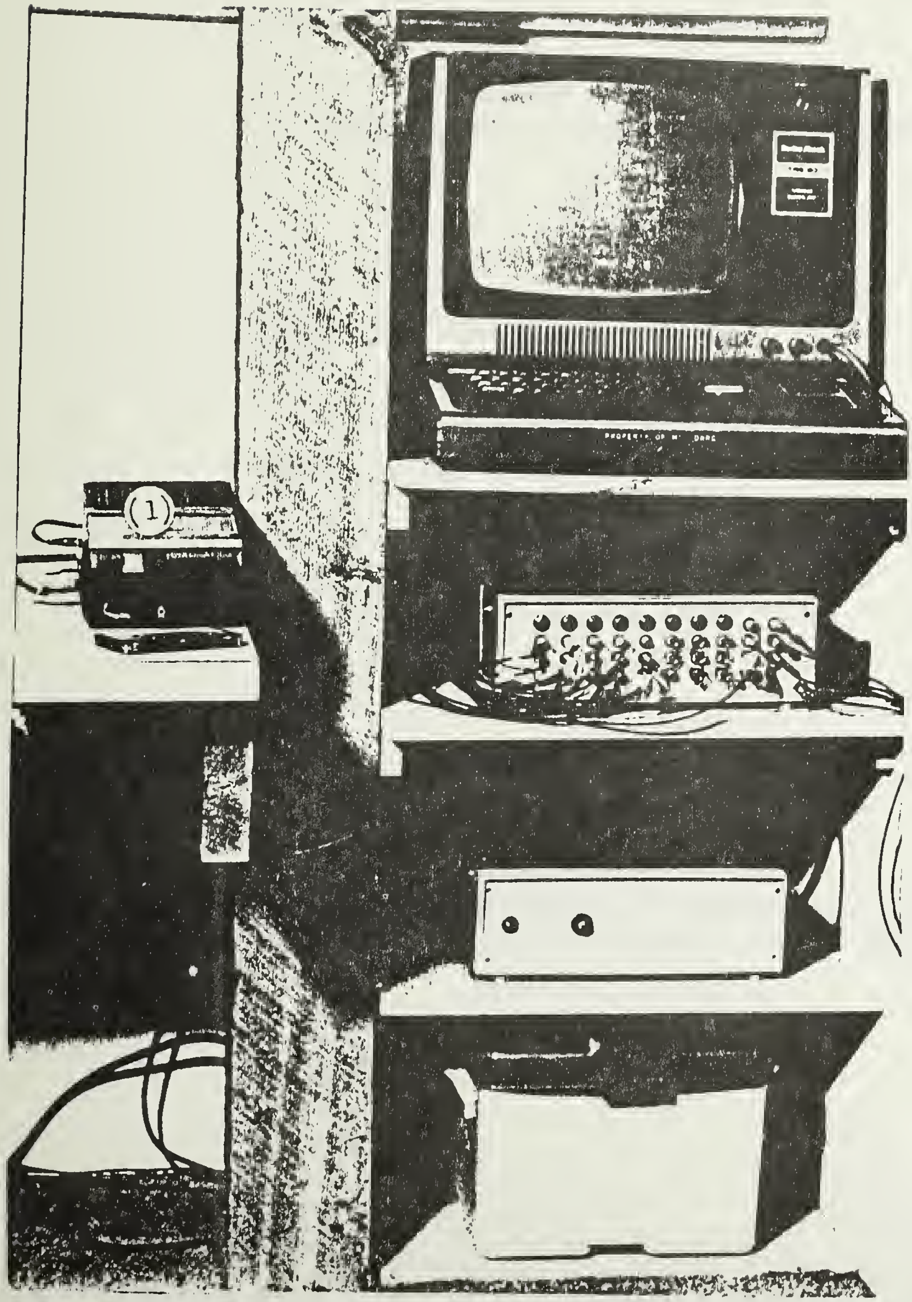


Figure 1: Computer-Based Data Acquisition System

THERMAL PERFORMANCE

OF THE BROWN PASSIVE SOLAR GREENHOUSE

by

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for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM

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NOTE ON UNITS

The test results in this report are given in metric or SI units. This convention corresponds to current professional practice and is in accord with the recommendations of the International Solar Energy Society and most technical journals.

Most readers are familiar with the Celsius or Centigrade temperature scale (^{o}C) and with power measured in kilowatts (kW). The metric unit of energy is the Joule (J). Most energy quantities in this report are expressed in megajoules (MJ) which is 10^6 joules or a million joules (1,000 BTU = 1 kBTU = 1.05 MJ). Since one MJ is about one thousand BTU's, a furnace with a rating of 100 thousand BTU/hour would be rated at about 100 MJ/hour. This approximate conversion will be useful to the reader accustomed to thinking in thousands of BTU.

Other abbreviations included in this report are: l = liters, m = meters, m^2 = square meters and kWh = kilowatt hours.

ABSTRACT

This project is a large, passive solar greenhouse located about 10 miles north of Circle, Montana. The greenhouse belongs to John Brown and was designed and built by Jim Baerg. The structure is well insulated, earth sheltered and has a large solar aperture. There was no source of auxiliary heating during the monitoring period. The project is a strongly solar driven structure leading to large temperature swings. The lack of auxiliary heat resulted in freezing temperatures within the structure during extreme cold periods with low solar radiation. Measurements of wind speed at the site showed that the existing wind generator could be used in conjunction with a resistance heater to provide a large portion of the auxiliary heating requirements. Given a modest amount of auxiliary heat and plants which could survive fluctuating temperatures, this structure could be powered 100% by solar and wind energy.

SOLAR SYSTEM

Type: Passive, earth sheltered
Aperture Area: 54 m^2 (gross), 40 m^2 (net)*
Glazing: Glass, fiberglass, vinyl
Movable Insulation: Foilon/Polarguard quilt, approximately 2.5 cm. thick

STORAGE MASS	THERMAL CAPACITY (MJ $^\circ C^{-1}$)
Water Barrels: 1872 kg	7.8
Rock Bin: 15,000 kg	12.3
Back Wall: 13,600 kg	11.4
Floor: 20,000 kg	36.1

AUXILIARY HEAT

None

*Shading from insulating curtain and framing

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TABLES

FIGURES

1.0 INTRODUCTION

This project is located 10 miles north of Circle, Montana. The greenhouse is owned by John Brown and was designed and built by Jim Baerg. The greenhouse is not connected to utility power and there is no auxiliary source of heat. Electricity for pumping water and lighting comes from a wind generator coupled with storage batteries. This project was monitored for 70 days during the winter of 1979-80.

2.0 DESCRIPTION OF PASSIVE SOLAR GREENHOUSE

A photograph of the greenhouse is shown in Figure 1. The slanted portion of the glazing is corrugated fiberglass and the vertical portion is glass. An interior glazing made of vinyl film was added to reduce convection losses through the aperture. The overall area of the aperture is 54 m^2. Shading due to the framing and movable insulation reduces the effective aperture to about 40 m^2.

Figure 2 shows a sectional view of the greenhouse. The north wall of the greenhouse is earth sheltered and the floor is dirt. An active heat-storage system consisting of a rock bin is located under the floor along the front boundary of the greenhouse. A thermostatically controlled fan draws warm air from the ridge of the greenhouse and distributes this air through a perforated pipe buried in the bottom of the rock bed. This air returns to the greenhouse through the exposed top surface of the rock bed. Direct current from the wind generator system drives the fan motor. Twelve drums filled with water are situated behind the glazing to serve as heat storage elements. Two wind-driven vents are intended to remove excess heat from the greenhouse. These vents were closed during the monitoring period.

Figure 3 shows a plan view and elevation view of the greenhouse which illustrates the location of the heat storage barrels. Note that the movable insulation shades a portion of the glazing. The photograph in Figure 4 shows the movable insulation in its retracted position. The movable insulation is supported on tracks and is actuated by hand. The curtain is constructed of two layers of Foilon quilted to a layer of 1.5 oz. Polarguard. When the curtains are in the closed position, spring

loaded boards clamp the edge of the curtain to reduce convection behind the curtain. One of these boards can be seen in Figure 4.

There are two types of growing beds in the greenhouse. The raised beds consist of dirt in wood-framed boxes about one meter above the floor of the greenhouse. In the west end of the greenhouse there are two beds on the floor of the greenhouse.

3.0 INSTRUMENTATION LAYOUT

Figure 5 shows a schematic of the greenhouse which depicts the arrangement of the transducers and the conceptual model of the storage masses for this project. A solar radiation transducer was mounted on the outside of the glazing and a second transducer on the inside of the glazing. These transducers were tilted to match the average slope of the glazed aperture. Details on the data acquisition system are shown in Appendix II. Figure 6 shows a picture of the data acquisition system located in the east end of the greenhouse. Figure 6(b) shows the mounting of the anemometer on one of the roof towers to measure wind speed.

A set of three averaging temperature probes was taped to the exterior surface of three different water storage barrels. These transducers were mounted using silicone heat transfer paste and then insulated from the room air with foam one cm. thick. The mounting of these probes was designed to assure that they would respond to the temperature of the water in the barrels. Two probes with radiation shields measured the air temperature in the east and west ends of the greenhouse near the glazing, about 3 m above the floor. A set of three temperature probes measured the air temperature in the rear portion of the greenhouse, about 2 m above the floor.

The fan used to charge the rock bin storage was instrumented with a status relay on the motor. A temperature probe was mounted in the duct to measure the inlet air temperature and three temperature probes buried 5 cm beneath the surface of the rock storage bed measured the outlet air temperature. The air flow in the duct used to charge the rock bed storage was measured using a hot-wire anemometer. The results of these measurements are shown in Figure 7. The average flow rate

was 21.75 m^3 per minute.

The soil temperatures in the raised growing beds and in the floor beds were measured with probes buried 5 cm below the surface of the soil. The temperature of the concrete wall at the rear of the greenhouse was measured with a set of three probes attached to the surface of the concrete and insulated with 1 cm of foam. The ambient air temperature was measured with a probe situated in a radiation shield attached to the north side of the center vent tower above the greenhouse. Further descriptions of the mounting probes are given in the Transducer Log in Table 2.

4.0 DATA ANALYSIS AND RESULTS

The raw, hourly data for the entire monitoring period was formulated using the format illustrated in Table 3. This data is for the day of December 30 and is used as an example to discuss typical data processing. A complete listing of the hourly data for this monitoring project is given in Appendix I. The data is organized around the energy balance shown in Equation [1].

$$\text{Energy Input} + \Delta\text{Stored Energy} = \text{Energy Output} \qquad [1]$$

The only energy input in this project is due to solar radiation passing through the aperture, as there is no auxiliary heat in the building. In Table 3, SOLAR INPUT was calculated from the measured insolation passing through the aperture multiplied by the effective area of the aperture for all times when the movable insulation was open.

Four heat storage elements were considered in this data analysis: the rock bin storage, the water barrels, the rear concrete wall and the floor of the greenhouse itself. These storage energy terms are positive when they are delivering heat to the air in the greenhouse and are negative when they are absorbing heat from the greenhouse.

The heat input into the rock bed is shown in Column 2, ROCK STORE. This quantity was obtained by multiplying the air flow rate in the forced convection duct by the specific heat and the inlet temperature to the rock bed minus the outlet temperature from the rock bed. Heat from

the rock bed was delivered back to the greenhouse by natural conduction and convection which was difficult to measure with precision. An approximate equation was derived to calculate the heat output of the rock bed based on the temperature difference between the rock bed and the air in the greenhouse. The results of this empirical equation are found in the third column, labeled ROCK OTPUT.

The water barrels, the storage wall and the floor of the greenhouse were considered as simple mass elements whose temperature and effective thermal mass was known. The heat input or output of each of these elements was calculated by multiplying the respective thermal masses by the hourly temperature difference.

The 7th column in the Table is labeled SUMM INPUT and is the algebraic sum of the solar radiation and storage elements listed previously. This term is the net hourly energy delivered to the greenhouse. The next column in the Table is labeled CALC LOSS and was calculated by multiplying the loss coefficient, Table 1, for the entire structure by the air temperature difference between the greenhouse and ambient air. The comparison of the magnitudes of SUMM INPUT and CALC LOSS tests the accuracy of the heat balance formulation. The disagreement of the hourly values of these two quantities is due to transient storage effects, approximations and errors in the analysis. These transient errors tend to cancel out in the daily averages and monthly averages (see data in Appendix I).

The next nine columns are hourly measurements of temperatures. AMBT TEMP is the ambient air temperature. The next column, INSL CURT, is the reading of a probe situated between the movable insulation and the glazing. The readings of this probe were used to figure the effective U value of the insulating curtain at night when it was closed. REAR TEMP and FRONT TEMP are the air temperatures in the rear and the front of the greenhouse. Notice that during the middle of the day, the temperature in the front of the greenhouse responds dramatically to the solar radiation input while the temperature in the rear is more stable. The next two columns show the temperatures in the planting beds on the floor, LOW BED, and the soil in the raised planting beds, HIGH BED.

The wind speed (in meters per second) measured on the tower on the greenhouse is shown in the right-hand portion of the table. Since there

is a wind generator at this site, we used the measured wind speed to calculate approximately the wind power in megajoules available at the site. The measured wind speed was modified to account for the extra heighth of the tower and a conversion efficiency of 35% was assumed for the wind generator. Since the wind generator is seldom used at this project, it represents a potential alternative source of power.

The final value, labeled CURT U-VAL, is the calculated heat transfer coefficient of the movable insulation in watts per square meter degrees Celsius. This value is calculated for all times when the curtain is closed. These measured values show that the curtain is considerably less effective than expected. This is probably due to air leakage around the edges of the curtain.

An overview of this table shows the storage elements delivering heat to the greenhouse during the early morning. During the day, when the sun is out and the curtains are open, the storage elements are all absorbing heat as signified by the negative numbers. When the sun goes down and the curtain is closed, the storage elements again deliver heat to the greenhouse.

The bottom line of this Table shows daily totals of energy quantities and daily averages of temperature quantities. For this day, a total of 430 MJ of solar energy was transmitted through the glazing. The heat requirement of the greenhouse was about 404 MJ. The sun, therefore, supplied an adequate amount of heat on this day. The storage elements served to absorb excess solar heat during the day and delivered heat to the greenhouse at night, as intended.

The temperature swings in the greenhouse are quite large. The temperature in the front portion of the greenhouse reached 33.6 °C at 2:00 p.m. (1400 hours), while the daily average temperature in the front of the greenhouse was 19.6 °C.

Graphical presentation of the data for this passive structure is shown in Figures 8, 9 and 10. Each of these figures shows continuous hourly data for five days. On the bottom of the graphs is the intensity of the solar radiation measured both on the outside of the glazing and inside the glazing. On days when the insulating curtain was not removed, there is only a single trace of solar radiation originating from the

outside solar cell. This occurs on January 2, January 9 and January 10.

In Figure 8, the first three days show a moderate amount of solar radiation available. The structure responds with increasing air temperatures during the day which decay over the night. The temperature of the soil in the low bed is shown to respond to a lesser magnitude and more slowly than the air temperature. Figure 9 shows three days of moderate solar radiation followed by two days when the curtains were not opened. Notice that the air temperature of the greenhouse drops to near zero degrees Celsius at the end of this period! The ambient temperatures are also quite low during this period. In Figure 10, the ambient temperatures rise through the week and there is usable solar radiation each day. The temperature of the soil gradually increases throughout this week.

The hourly data of Appendix I is condensed into daily total and average values and presented in Tables 4, 5 and 6. The format of this Table has been changed slightly to include two new columns, LOW TEMP and HIGH TEMP. These columns show the maximum and minimum daily readings of the temperature probes in the rear of the greenhouse. These data are included to indicate thermal stress on plants growing in the greenhouse.

Notice that on January 11, the temperature in the rear of the greenhouse dropped below freezing. Inspection of the hourly data for January showed that temperatures in the front portion of the greenhouse, which are less stable, dropped below freezing on seven different days.

A graphical presentation of the daily average temperature data for December and January is given in Figures 11 and 12. Shown on these graphs are the daily average ambient air temperatures and air temperatures inside the greenhouse. Bars on the inside temperatures indicate the maximum and minimum values of air temperature measured at the rear of the greenhouse. The bar chart in the lower portion of the graph shows the corresponding solar energy input into the house each day in megajoules. These graphs illustrate the combined effect of low ambient temperatures and low solar radiation on the equilibrium temperature of the growing space inside the greenhouse. The graphs also indicate the wide temperature swings in the greenhouse on days when there is a large amount of solar radiation.

The data is further condensed to form an overall performance summary and shown in Table 7. The solar gain for the entire monitoring period of 70 days agrees quite well with the calculated heat load, which verifies the analysis. The storage heat flow terms cancel out in this overall analysis. The average air temperature inside the greenhouse throughout the monitoring period was 14.1 °C, while the average ambient temperature was -7.8 °C. It is important to note that during January the air temperature in portions of the greenhouse was below freezing for seven days.

The average temperatures of the high and low plant beds are also given. The high bed is seen to have an average temperature of 1.3 °C above the low bed temperature. It should be noted that during January the low bed was freezing on two days. The high bed responds more dramatically to heat gains during the day but is more subject to freezing during extended cloudy and cold periods.

The last column in the Summary Table gives the estimated heating potential of the wind generator. This would be accomplished if the wind generator was allowed to run 100% of the time and was connected to resistance coils located in the greenhouse. The analysis shows that during the monitoring period the wind generator would have provided 3,495 MJ of heat to the greenhouse. The effect of this additional energy input on the average temperature of the greenhouse is listed in the final column, headed ΔT, °C. This column shows the estimated increase in average temperature if the wind generator was used to heat the greenhouse. Although this analysis is highly approximate, it indicates that this extra energy may have prevented the greenhouse from freezing.

5.0 CALCULATED PERFORMANCE

A prediction of the performance of this project was made using a modified version of the f-chart design analysis. Solar radiation data was taken from the Solar Insolation Measurement, Montana (SIMM) station at Glendive. Temperature and average degree-day data from Glendive was also used. This design procedure shows that the annual solar fraction of the greenhouse would be 85%, Table 8.

The analysis assumes that auxiliary or backup energy is used to

maintain the temperature of the greenhouse at 18.3 °C. The results show that auxiliary energy is needed during the months of December, January and February. The measured average air temperature in the greenhouse did drop below this set point during the monitoring period. Calculations of the auxiliary energy required to raise the greenhouse from the measured temperature to the set point of 18.3 °C showed a total energy requirement of 1,379 kWh. The f-chart prediction for auxiliary energy for the corresponding period was 1,814 kWh. The wind energy available during the monitoring period was 970 kWh.

It appears that a modest amount of auxiliary energy would prevent this structure from freezing, an important consideration for a greenhouse. This auxiliary energy load could approximately be met by the existing wind generator coupled to appropriate heat storage. This option is particularly attractive since the design goal for this greenhouse was a 100% alternative energy structure.

TABLE 1

CALCULATED HEAT LOAD FOR PASSIVE GREENHOUSE

	AREA, FT^2	R	U	UA
Roof	700	32	0.031	21.9
$Wall_1$	96	22	0.045	4.4
$Wall_2$	80	4.7	0.22	17.1
Collector	585	4.67 (1.67)	0.214 (0.60)	125.3* (351) **
Floor & Back Wall		Negligible		0
Infiltration (est.)				58

* 0.86 MJ hr^{-1} $^oC^{-1}$
452 BTU hr^{-1} $^oF^{-1}$

** 0.43 MJ hr^{-1} $^oC^{-1}$
227 BTU hr^{-1} $^oF^{-1}$

* Insulating curtain closed
** Insulating curtain open

TABLE 2
TRANSDUCER LOG

BROWN GREENHOUSE

TYPES:

S - SOLAR
T - TEMP
DT - DUCT TEMP
ST - STATUS
P - POWER

DISK #	RS #	PROBE #	TYPE	LOCATION AND MOUNTING
1	1	2	S	Outdoor Solar Transducer: Mounted on vent tower 1.5m above the peak of the roof
2	5	5	S	Indoor Solar Transducer: Mounted 2m above Greenhouse floor
3	6	Manual Switch	ST	Manual Switch to indicate Curtain Status: Located next to light switch
4	7	relay	ST	Relay connected in parallel with fan motor to indicate fan status
5	8		ST	Calculated Curtain Status
6	16			Anemometer: Used to measure wind speed. Mounted on vent tower .5m above vent
7	29	2 7, 51	T	Averaging Probes: Located on 3 of 9 55-gallon drums filled with water for heat storage
8	30	22 23, 24	T	Set of 3 Averaging Probes: Located on the north side of supporting posts
9	31	26 27, 28	T	Averaging Probes: Buried 6-8 inches in Rock Bin
10	32	30 32, 33	T	Averaging Probes: Located on inside of North Wall
11	34	41	T	Temperature probe mounted .5m below peak of ceiling in radiation shield
12	35	42	DT	Temperature probe located in duct just beneath the fan
13	36		DT	Above probe zeroed on status
14	37	44	T	Temperature probe located in growing bed bed on Greenhouse floor 5 cm beneath soil surface
15	38	48	T	Temperature probe located in growing bed 1m above floor, 5cm beneath soil surface
16	39	49	T	Temperature probe located between glazing and insulating curtain 1.5 meters above floor
17	40	50	T	Ambient Temperature Probe: Mounted on north side of vent tower 1m above the roof

TABLE 3

TYPICAL HOURLY DATA

DAILY PERFORMANCE SUMMARY FOR BROWN'S GREENHOUSE 12/ 30 R= 523

HR	SOLAR INPUT (MJ)	ROCK STORE (MJ)	ROCK OTPUT (MJ)	STORE BARRL (MJ)	STORE WALL (MJ)	STORE FLOOR (MJ)	SUM INPUT (MJ)	CALC LOSS (MJ)	AMBT TEMP (C)	INSL CURT (C)	REAR TEMP (C)	FRONT TEMP (C)	LOW BED (C)	HIGH BED (C)	ROCK BED (C)	BACK WALL (C)	BARRL TEMP (C)	WIND SPEED (M/S)	WIND POWER (MJ)	OVRL U-VAL (W/M2 C)
1	.0	.0	2.4	1.4	2.2	9.7	15.7	10.6	-7.2	-.0	17.6	15.2	15.8	19.7	11.4	15.7	17.1	3.7	.7	1.8
2	.0	.0	2.3	1.5	2.2	9.4	15.4	10.7	-7.7	-.5	17.1	14.9	15.6	19.3	10.9	15.5	16.9	4.0	.9	1.8
3	.0	.0	2.2	1.5	2.0	9.0	14.8	10.9	-8.7	-1.1	16.7	14.3	15.3	19.8	10.4	15.3	16.7	3.5	.6	1.9
4	.0	.0	2.1	1.6	2.3	8.7	14.6	11.3	-10.0	-1.6	16.3	13.9	15.1	18.4	9.9	15.1	16.5	3.0	.6	2.1
5	.0	.0	2.0	1.6	2.2	7.6	13.3	10.7	-9.6	-1.8	15.9	13.5	14.9	18.0	9.5	15.0	16.3	4.3	1.1	1.8
6	.0	.0	1.9	1.6	2.0	7.5	13.1	11.1	-10.2	-2.3	15.6	13.1	14.6	17.5	9.1	14.8	16.1	4.5	1.1	2.0
7	.0	.0	1.8	1.6	2.0	7.2	12.7	10.9	-10.3	-2.5	15.2	12.8	14.4	17.2	8.7	14.5	15.9	4.2	1.1	2.0
8	.0	.0	1.6	1.6	2.0	7.2	12.4	10.7	-10.1	-2.3	14.9	12.5	14.2	16.8	8.3	14.4	15.7	4.7	1.4	2.0
9	20.2	-2.3	-5.2	.5	1.3	6.9	21.3	22.7	-9.7	9.9	16.6	14.5	14.1	16.5	9.5	14.3	15.6	3.5	.6	.0
10	69.1	-6.7	-14.0	-2.4	-.7	-8.3	37.0	26.0	-6.9	19.9	23.3	23.6	14.3	17.2	12.5	14.4	15.9	3.5	.6	.0
11	92.2	-10.9	-8.3	-4.5	-5.8	-23.9	33.7	27.4	-4.9	34.0	27.3	31.6	15.1	19.6	14.3	14.9	16.5	3.7	.7	.0
12	65.2	-10.3	-6.4	-3.9	-9.4	-35.5	-.3	27.9	-4.5	34.8	30.1	31.7	16.1	22.0	15.7	15.7	17.0	4.2	1.1	.0
13	69.1	-10.4	-5.2	-4.4	-12.9	-30.7	5.6	27.9	-3.4	35.7	31.3	33.1	15.9	23.7	16.9	16.8	17.6	4.1	.9	.0
14	70.6	-9.9	-3.9	-3.8	-5.3	-23.5	24.2	29.2	-2.5	37.0	31.5	33.6	17.6	24.7	17.7	17.3	18.1	4.6	1.3	.0
15	24.5	-6.1	-2.7	-2.3	1.6	-17.3	-2.4	27.1	-2.5	30.7	27.1	27.6	18.1	25.1	18.3	17.2	18.3	4.7	1.4	.0
16	18.7	.0	1.7	-1.0	2.3	-3.6	18.1	25.1	-3.3	25.5	27.1	25.6	18.2	24.6	17.9	17.0	19.5	4.3	1.1	.0
17	.0	.0	3.8	1.3	2.4	7.9	15.5	12.5	-5.1	7.9	23.9	21.8	18.0	23.7	17.1	16.8	18.3	3.4	.7	3.5
18	.0	.0	4.9	1.3	2.6	14.1	22.9	12.3	-6.7	3.0	21.9	19.6	17.6	22.7	16.0	16.5	18.1	2.9	.3	2.2
19	.0	.0	4.8	1.4	2.4	13.7	22.3	12.1	-7.6	1.6	20.5	18.2	17.2	21.8	15.0	16.3	18.0	2.6	.2	2.2
20	.0	.0	4.1	1.3	2.3	12.6	20.3	11.7	-7.7	.7	19.5	17.1	16.8	21.1	14.1	16.1	17.8	4.3	1.1	2.6
21	.0	.0	3.5	1.3	2.2	11.6	18.6	11.4	-7.8	-.1	18.7	16.2	16.5	20.4	13.3	15.9	17.6	3.5	.6	1.8
22	.0	.0	3.1	1.6	2.2	11.6	18.4	12.3	-10.6	-.8	18.0	15.5	16.2	19.8	12.6	15.7	17.4	.2	.0	2.3
23	.0	.0	3.0	1.6	2.7	10.5	17.2	12.2	-11.0	-1.6	17.4	15.0	15.9	19.3	12.0	15.5	17.2	1.8	.1	2.2
0	.0	.0	2.9	1.6	2.0	10.1	16.6	12.0	-11.1	-2.3	16.9	14.4	15.6	18.8	11.4	15.4	17.0	.0	.0	2.0
	430.6	-56.7	2.4	1.9	6.1	16.6	400.9	403.6	-7.4	9.5	21.0	19.6	16.0	20.3	13.0	15.7	17.1	3.5	19.1	

TABLE 4

DAILY SUMMARY DATA FOR DECEMBER

DAILY PERFORMANCE SUMMARY FOR BROWN'S GREENHOUSE

DA	SOLAR INPUT (MJ)	ROCK STORE (MJ)	ROCK OUTPUT (MJ)	STORE BARREL (MJ)	STORE WALL (MJ)	STORE FLOOR (MJ)	SUMM INPUT (MJ)	CALC LOSS (MJ)	AMBT TEMP (C)	FRONT TEMP (C)	REAR TEMP (C)	* LOW TEMP (C)	* HIGH TEMP (C)	LOW BED (C)	HIGH BED (C)	ROCK BED (C)	BACK WALL (C)	BARREL TEMP (C)	WIND SPEED (M/S)	WIND POWER (MJ)
7	325.4	-37.5	6.2	-7.0	-10.1	-39.7	237.4	279.4	-6.3	12.6	14.6	9.6	26.7	10.3	11.3	6.4	9.8	9.1	4.5	24.2
8	331.6	-67.3	-24.5	-17.3	-20.0	-55.2	197.3	209.3	1.2	15.5	16.5	10.2	29.1	11.5	13.8	8.7	11.2	10.4	4.2	27.2
9	302.4	-48.6	-9.9	-13.2	-9.4	-23.2	193.0	154.7	6.7	16.4	17.8	13.1	29.1	12.7	15.7	11.8	12.4	12.6	4.1	24.9
10	25.9	.0	39.4	22.3	23.3	99.3	215.2	229.7	-4.1	10.5	13.3	10.1	15.7	11.8	13.1	9.6	11.8	12.3	6.6	127.5
11	593.2	-16.7	-1.0	-4.0	-8.9	-52.0	500.7	423.5	-15.8	13.0	14.9	8.5	28.3	11.4	13.0	4.2	10.8	10.7	4.1	35.9
12	57.6	.0	.9	21.5	23.2	78.0	181.1	203.5	-6.0	8.3	10.7	9.2	13.3	10.4	10.6	4.7	9.9	9.7	4.8	67.2
13	237.6	-43.8	-13.0	-4.2	-9.7	-38.3	123.6	220.1	-10.5	11.1	12.7	7.6	24.7	10.3	10.8	6.2	9.5	8.3	.6	2.2
14	354.2	.0	.0	-14.6	-17.2	-53.8	268.7	226.9	-1.3	15.3	16.4	10.1	33.0	11.7	13.7	7.4	10.8	10.0	4.5	35.1
15	.0	.0	39.9	49.5	55.9	165.3	310.4	311.1	-22.1	5.3	8.0	4.9	12.4	9.6	9.4	2.1	8.8	7.9	3.4	95.1
16	527.0	.0	-9.2	-4.2	-7.3	-37.9	619.5	278.2	-19.0	8.9	9.9	3.2	25.4	8.5	8.1	-1.1	6.9	4.4	2.3	22.0
17	92.2	.0	-15.6	-5.3	-3.1	2.2	76.3	87.4	1.2	12.7	9.7	7.3	15.6	8.5	8.0	2.2	7.1	5.2	3.6	13.2
18	517.0	-55.0	-23.5	-35.4	-44.0	-139.3	219.8	155.5	7.3	23.6	19.3	9.3	35.9	10.9	13.5	6.3	9.6	8.6	4.3	33.6
19	455.0	-98.7	-12.4	-25.6	-27.5	-49.8	245.9	220.4	3.9	19.9	20.1	12.6	34.9	13.1	17.5	10.6	12.4	11.8	3.9	22.1
20	131.0	.0	9.6	3.5	10.5	47.3	201.3	173.7	3.1	15.8	16.6	14.3	22.6	13.0	15.2	10.6	12.7	13.6	3.4	14.9
21	456.5	-77.9	-8.3	-11.3	-12.1	-50.2	276.7	265.1	.6	19.1	19.1	12.5	31.3	13.4	16.9	11.6	13.0	13.7	3.1	13.9
22	469.8	-33.0	1.3	-8.2	-8.2	-23.9	378.9	320.2	-1.8	56.1	20.4	13.6	35.0	14.6	13.7	11.4	13.9	15.1	1.8	7.5
23	.0	.0	15.3	28.8	32.2	117.3	193.6	201.9	-5.9	11.1	13.7	12.1	14.6	12.6	14.3	8.9	12.4	13.6	2.6	11.2
24	171.4	.0	.2	6.9	5.3	-1.8	183.9	221.3	-3.4	11.7	13.7	10.8	21.9	11.5	12.2	7.3	11.0	11.1	2.2	9.2
25	56.2	.0	-1.7	7.4	8.9	24.2	94.9	172.6	1.8	10.2	12.5	11.4	15.1	11.6	11.2	7.8	10.2	10.2	3.1	12.7
26	493.9	.0	-.7	-22.9	-32.9	-112.3	325.2	222.7	.6	19.4	19.5	10.9	35.9	12.7	15.3	9.4	11.8	11.7	3.8	19.3
27	598.3	-97.7	-9.9	-17.5	-14.5	-34.7	424.1	336.0	-2.9	20.2	20.8	12.6	35.3	14.5	13.7	10.5	13.7	13.7	3.4	15.5
29	499.7	-92.2	-9.0	-19.1	-21.6	-53.8	304.6	255.7	-2.0	27.4	27.0	13.2	37.9	17.0	27.2	15.1	14.7	17.5	3.2	8.2
30	430.6	-54.7	2.4	1.9	6.1	16.6	432.9	423.6	-7.4	19.6	21.6	14.9	31.5	15.0	20.3	13.0	15.7	17.1	3.5	13.1
31	240.5	-42.4	.5	9.7	11.0	20.4	232.9	314.2	-7.1	17.7	19.6	14.0	23.5	15.1	13.2	11.6	14.6	16.0	3.9	19.5

*Extremes of REAR TEMP

TABLE 5

DAILY SUMMARY DATA FOR JANUARY

DAILY PERFORMANCE SUMMARY FOR BROWN'S GREENHOUSE

DA	SOLAR INPUT (MJ)	ROCK STORE (MJ)	ROCK OTPUT (MJ)	STORE BARRL (MJ)	STORE WALL (MJ)	STORE FLOOR (MJ)	SUMM INPUT (MJ)	CALC LOSS (MJ)	AMBI TEMP (C)	FRONT TEMP (C)	REAR TEMP (C)	LOW TEMP (C)	HIGH TEMP (C)	LOW BED (C)	HIGH BED (C)	ROCK BED (C)	BACK WALL (C)	BARRL TEMP (C)	WIND SPEED (M/S)	WIND POWER (MJ)
1	400.3	-69.1	-9.4	-4.8	-4.7	-17.0	273.3	277.6	-1.2	19.3	20.3	14.4	33.7	15.4	19.7	17.2	14.8	15.9	4.0	26.1
2	.0	.0	27.3	30.5	33.2	121.7	217.7	219.1	-7.6	11.1	13.6	11.7	16.2	13.5	14.5	9.8	12.9	14.4	4.4	71.0
3	277.9	.0	-1.5	3.3	-5.0	-23.2	245.5	247.1	-3.5	13.9	15.5	10.8	32.5	12.7	13.4	7.6	11.8	12.6	5.2	47.2
4	.0	.0	12.9	21.4	26.1	84.5	144.9	196.7	-7.7	8.7	11.4	10.0	13.0	11.5	11.1	6.3	10.6	10.5	4.7	63.1
5	.0	.0	5.3	17.6	19.2	50.9	93.5	190.8	-8.3	6.5	9.2	8.2	9.9	9.3	8.6	4.4	8.7	9.1	3.9	29.3
6	185.8	.0	25.3	26.3	25.1	49.5	311.9	357.2	-21.6	5.7	7.4	5.2	13.9	8.5	6.4	.9	6.5	5.5	.0	.0
7	357.1	.0	3.9	13.7	5.6	5.1	385.3	464.2	-26.0	6.5	8.0	3.9	19.9	8.0	6.5	-1.6	5.6	2.9	.0	.0
* 8	272.3	.0	8.3	9.6	9.8	35.7	355.7	452.4	-27.0	4.3	6.3	2.0	17.7	7.2	5.5	-3.2	4.7	1.5	.0	.0
* 9	.0	.0	-4.1	14.6	21.5	71.5	103.4	251.1	-25.0	.3	2.8	1.8	6.0	5.5	2.1	-4.0	3.2	-.3	.0	.0
*10	.0	.0	5.0	11.0	17.1	50.2	83.7	234.3	-21.4	-1.6	1.3	.3	2.0	4.0	-.4	-3.5	1.6	-1.7	.0	.0
*11	417.6	.0	-6.6	-13.3	-21.3	-60.4	315.7	401.5	-24.0	4.5	5.8	-.4	21.4	4.4	2.6	-4.0	2.0	-1.3	.0	.0
*12	184.3	.0	-15.5	-10.8	-14.8	-34.7	108.6	131.5	-3.2	5.6	7.0	2.1	19.5	5.2	4.7	-1.9	3.2	-.1	3.1	33.2
13	200.2	.0	-5.0	-11.6	-17.8	-31.9	134.1	155.5	-1.6	8.4	10.1	6.2	24.0	6.5	7.4	.8	5.1	1.5	5.3	18.4
14	410.4	-37.1	-16.7	-24.9	-33.9	-93.9	203.1	277.5	-.2	14.7	15.1	7.0	35.4	9.1	11.3	2.9	7.3	7.5	3.1	20.7
15	491.0	-28.0	-7.5	-30.1	-27.7	-72.9	322.9	322.5	-.3	13.7	18.9	10.0	37.8	10.6	16.1	5.6	10.3	7.4	4.4	[illegible]
16	479.5	-95.5	-12.9	-19.1	-11.2	-31.0	309.9	223.1	-2.7	17.7	18.5	11.2	35.2	11.8	17.3	8.6	11.9	10.2	3.4	52.5
17	203.8	-49.3	-.2	-2.6	13.0	18.1	187.7	232.7	-1.6	15.9	16.9	12.3	25.3	11.8	14.2	9.5	11.5	11.6	5.2	76.9
18	.0	.0	22.8	20.9	25.8	96.4	165.0	177.2	-7.1	9.1	11.5	9.2	13.3	10.7	11.3	7.2	9.9	10.6	6.7	119.5
19	567.4	-94.1	-10.0	-15.0	-11.6	-91.3	355.3	395.9	-12.4	15.9	16.4	7.7	32.5	10.7	13.8	6.6	9.1	10.0	4.6	35.4
20	.0	.0	8.4	6.5	5.9	42.6	63.5	53.6	-17.7	8.8	11.2	10.4	12.1	11.9	13.2	5.2	9.6	10.7	4.5	6.7
23	47.5	.0	-17.6	2.5	9.4	7.9	47.9	47.5	4.8	10.4	12.6	10.8	15.9	10.6	1.7	8.7	9.6	10.7	7.6	85.6
24	.0	.0	12.2	13.4	10.9	47.7	84.2	117.3	-1.0	9.0	10.4	8.4	13.5	9.5	1.5	7.4	8.1	9.3	9.5	271.2
25	.0	.0	22.5	19.8	16.4	45.8	104.5	235.5	-17.2	7.7	8.9	5.9	15.4	8.2	3.6	3.6	6.7	7.1	4.7	18.4
26	.0	.0	13.0	25.3	19.1	49.8	109.2	274.1	-22.0	5.4	6.5	4.0	12.7	6.9	5.1	-.2	5.1	6.2	6.1	155.9
*27	.0	.0	8.5	14.9	15.9	51.3	90.5	234.3	-27.5	2.3	4.1	2.3	8.0	5.4	3.5	-2.4	3.6	1.5	5.0	[illegible]
*28	620.4	.0	-5.3	-26.5	-24.2	-129.5	436.1	537.0	-27.7	11.1	11.2	1.1	27.4	7.1	5.1	-2.6	4.0	2.4	3.5	22.5
29	616.3	-108.9	-23.5	-21.6	-12.2	-14.9	437.3	540.4	-21.4	11.2	11.9	6.1	27.1	8.9	9.9	2.4	5.6	5.0	2.3	17.0
30	548.6	-91.6	-.9	-18.2	-14.1	-42.2	331.6	432.5	-18.0	13.2	13.3	5.4	27.8	9.4	10.9	3.7	6.7	7.4	6.1	[illegible]
31	483.2	-90.1	-11.3	-14.5	-14.2	-41.2	316.9	349.7	-11.6	15.1	15.2	7.4	27.9	10.3	12.4	5.5	7.9	9.6	4.4	31.7

*Temperature was below freezing in front of greenhouse

TABLE 6

DAILY SUMMARY DATA FOR FEBRUARY

DAILY PERFORMANCE SUMMARY FOR BROWN'S GREENHOUSE

DA	SOLAR INPUT (MJ)	ROCK STORE (MJ)	ROCK OTPUT (MJ)	STORE BARRL (MJ)	STORE WALL (MJ)	STORE FLOOR (MJ)	SUMM INPUT (MJ)	CALC LOSS (MJ)	AMBT TEMP (C)	FRONT TEMP (C)	REAR TEMP (C)	LOW TEMP (C)	HIGH TEMP (C)	LOW BED (C)	HIGH BED (C)	ROCK BED (C)	BACK WALL (C)	BARRL TEMP (C)	WIND SPEED (M/S)	WIND POWER (MJ)
1	.0	.0	5.5	19.8	13.4	101.1	139.7	155.5	-4.4	7.9	10.1	9.3	11.6	9.1	11.4	4.9	8.0	9.3	7.9	22.9
2	492.4	-93.2	-20.7	-25.6	-23.8	-119.5	198.6	176.0	-.4	16.7	16.6	9.1	31.5	10.2	11.0	8.3	8.4	9.9	4.0	35.0
3	.0	.0	4.8	9.8	5.3	57.8	77.7	116.6	2.0	11.7	13.3	11.9	16.7	10.4	12.7	8.7	9.3	11.0	4.6	158.1
4	470.9	-33.9	-4.7	-18.7	-16.0	-81.6	311.0	244.8	1.0	17.2	17.6	11.1	33.0	11.6	13.2	9.4	9.9	11.8	7.4	175.0
5	355.7	-66.2	-5.7	-6.9	-6.6	-72.0	248.3	276.9	-2.1	16.6	17.5	12.1	29.3	12.5	15.0	10.9	10.9	13.1	4.2	39.7
6	573.3	-97.2	-6.4	-19.8	-13.8	-47.3	436.8	400.9	-6.2	20.0	20.2	11.6	35.6	13.8	16.7	12.8	11.7	16.2	6.9	63.0
7	.0	.0	25.1	34.2	27.9	123.9	215.9	232.1	-9.9	10.4	12.6	10.7	14.8	11.9	14.9	9.9	11.0	13.9	2.2	25.1
8	596.2	-92.2	-41.8	-26.4	-18.5	-197.7	279.5	270.9	-5.2	18.9	18.3	9.6	33.1	11.6	12.1	9.0	9.9	12.1	5.1	34.4
9	28.8	.0	41.7	29.9	20.6	179.4	300.2	210.7	-4.5	10.8	12.9	11.0	15.1	11.5	12.9	8.7	10.2	12.3	7.2	93.4
10	351.4	-60.1	-1.6	-1.2	5.2	-32.1	261.6	426.3	-9.6	14.3	14.7	9.4	27.9	11.4	11.6	7.4	9.4	11.3	8.1	230.0
11	653.6	-76.9	-7.8	-19.1	-15.5	-66.8	457.6	456.7	-12.4	19.0	18.7	8.8	35.2	13.1	16.6	8.2	9.9	12.7	3.7	22.6
12	.0	.0	6.2	11.6	8.2	63.9	89.9	77.4	-7.5	10.5	12.5	11.8	13.6	12.4	20.1	7.9	10.3	13.2	4.9	19.2
13	103.1	.0	22.6	33.9	23.2	84.5	274.4	192.8	-13.0	9.3	11.1	7.8	16.3	10.2	12.7	4.7	7.9	9.1	7.0	69.9
14	187.2	.0	7.1	10.6	6.3	7.9	219.1	392.1	-19.2	8.7	10.4	6.3	19.2	9.6	11.6	2.2	7.1	7.5	4.8	42.5
15	376.1	.0	-2.3	-5.9	-8.0	-44.0	309.9	421.9	-16.1	11.7	12.8	6.0	23.5	10.0	12.3	1.5	7.1	7.1	5.5	46.5
16	453.7	-107.1	-23.2	-17.2	-13.7	-43.3	259.3	492.1	-16.3	15.5	15.6	6.8	31.7	11.0	15.4	4.7	8.0	8.3	3.7	20.9
17	409.0	.0	-.6	-18.6	-22.0	-50.5	317.3	465.0	-7.9	19.4	19.4	9.3	34.1	12.3	18.9	6.2	9.7	10.9	2.6	11.7
18	171.4	-46.2	-4.8	8.0	9.5	50.2	197.1	252.1	-4.9	13.4	14.9	11.9	24.3	12.3	17.6	7.7	10.3	11.6	4.6	37.1

TABLE 7

OVERALL SUMMARY FOR BROWN'S GREENHOUSE
12/7/79 to 2/17/80

Month	Days	Solar Gain	Calculated Heat Load	Average Temp.	Ambient Temp.	High Bed Temp.	Low Temp.	*** Wind Potential	
		MJ	MJ	°C	°C	°C	°C	MJ	ΔT, °C
December	24	7877	6272	15.6	- 3.6	14.3	12.5	738	2.3
January	29	6794	8178	*11.1	-12.1	**8.7	9.1	1606	4.5
Feburary	17	5063	4995	15.6	- 7.6	14.1	11.3	1151	5.34
	—	—	—	—	—	—	—	—	—
Total	70	19734	19445	14.1	- 7.8	12.3	11.0	3495	3.9

* Air temperature below freezing on 7 days

** Soil below freezing on 2 days

*** Estimated heating potential of wind-electric generator

TABLE 8

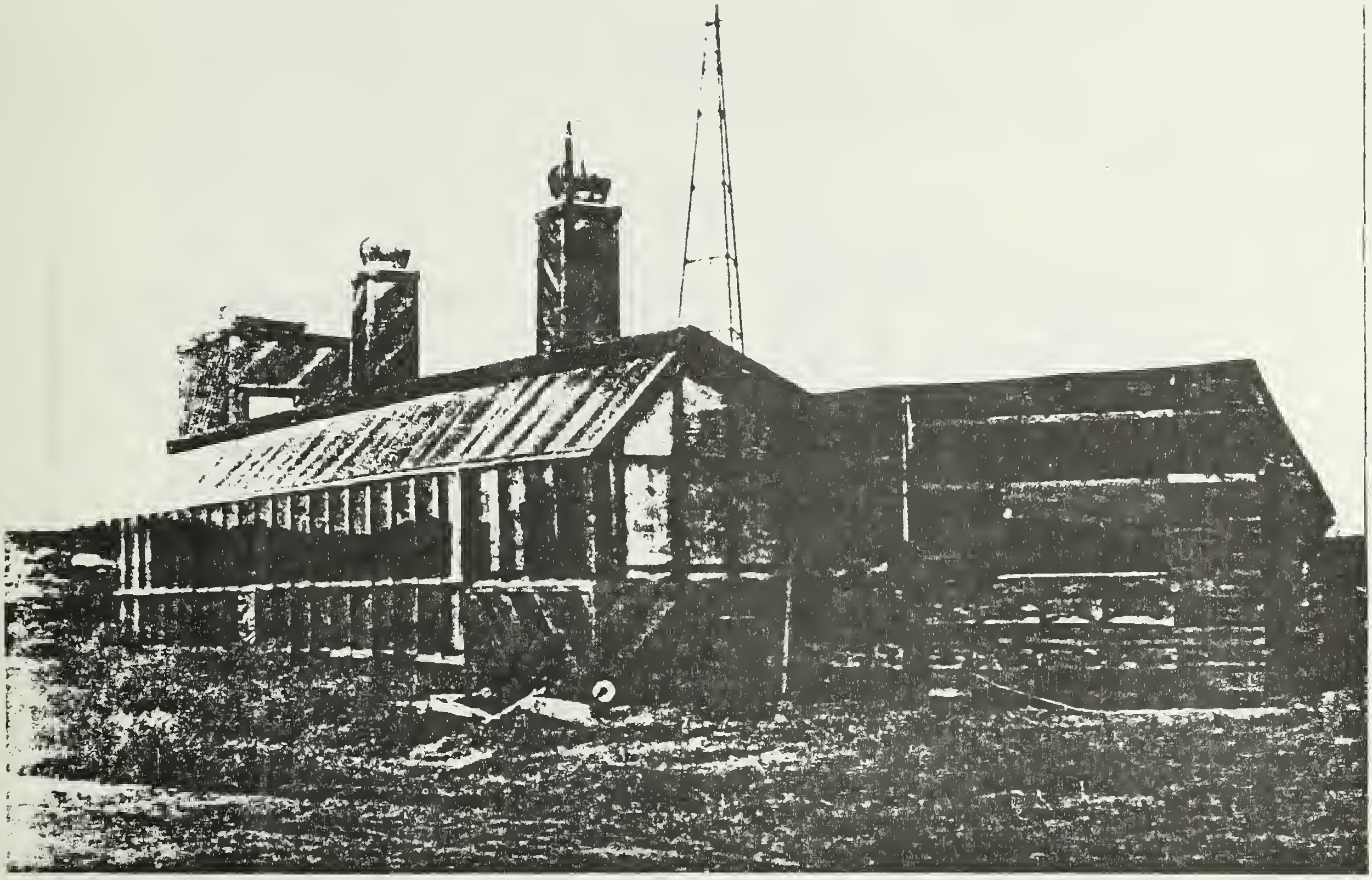
PREDICTED PERFORMANCE OF PASSIVE GREENHOUSE

	----DAILY----		---------------------MONTHLY---------------------						
MON	SOLAR RAD KWH/m2	AMBT TEMP (C)	DEGREE DAYS (C-DAY)	WATER LOAD KWH	HEAT LOAD KWH	TOTAL LOAD KWH	SOLAR FRAC (%)	SOLAR ENERGY KWH	BACKUP ENERGY KWH
JAN	3.3	-9.5	863	0	2899	2899	74	2157	742
FEB	3.3	-6.4	692	0	2326	2326	95	2217	109
MAR	3.9	-.9	596	0	2003	2003	100	2002	1
APR	3.7	8.0	313	0	1053	1053	100	1052	1
MAY	3.6	14.3	137	0	459	459	100	459	0
JUN	3.7	18.8	50	0	168	168	100	168	0
JUL	3.8	23.3	4	0	15	15	100	14	1
AUG	4.1	22.3	7	0	24	24	100	24	0
SEP	4.4	15.7	113	0	381	381	100	380	1
OCT	3.5	9.7	269	0	903	903	100	903	0
NOV	2.9	.6	532	0	1786	1786	100	1786	0
DEC	2.1	-5.6	742	0	2494	2494	48	1187	1307
YEAR	3.5	7.5	4318	0	14511	14511	85	12349	2162

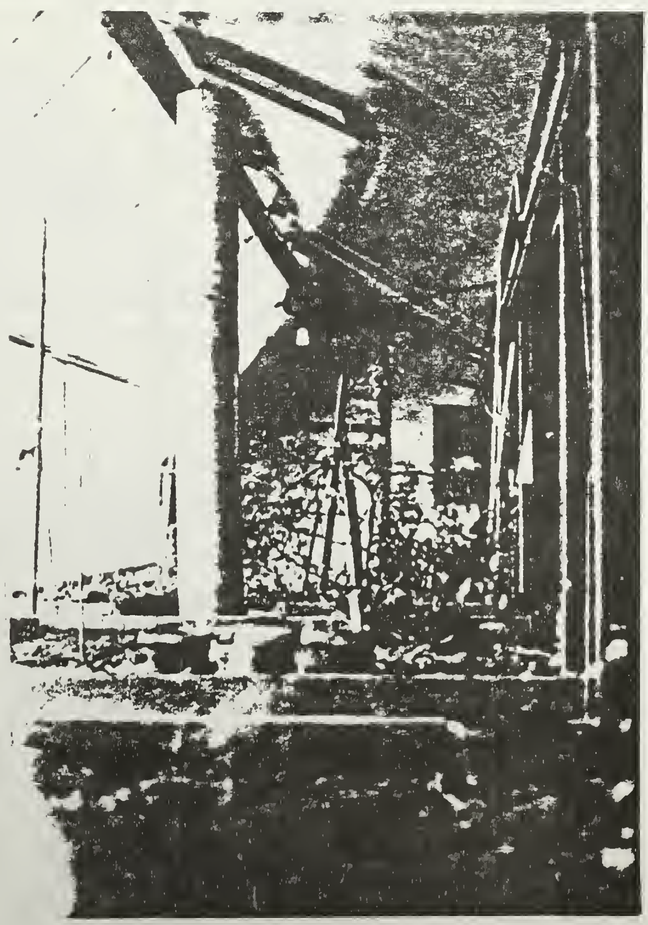
YEARLY SOLAR FRACTION.... .85

CLIENT.................... BROWN
LOCATION.................. GLENDIVE

COLLECTOR AREA............ 40.00 m2, 430.4 ft2
COLLECTOR TILT............ 78 DEGREES,
COLLECTOR TYPE............ AIR
EFFICIENCY SLOPE......... 3.21 W/C-m2, .56 BTU/F-ft2
Y-INTERCEPT.............. .69
HOUSE LOAD FACTOR........ .14 KWH/C-HOUR, 265 BTU/F-HOUR

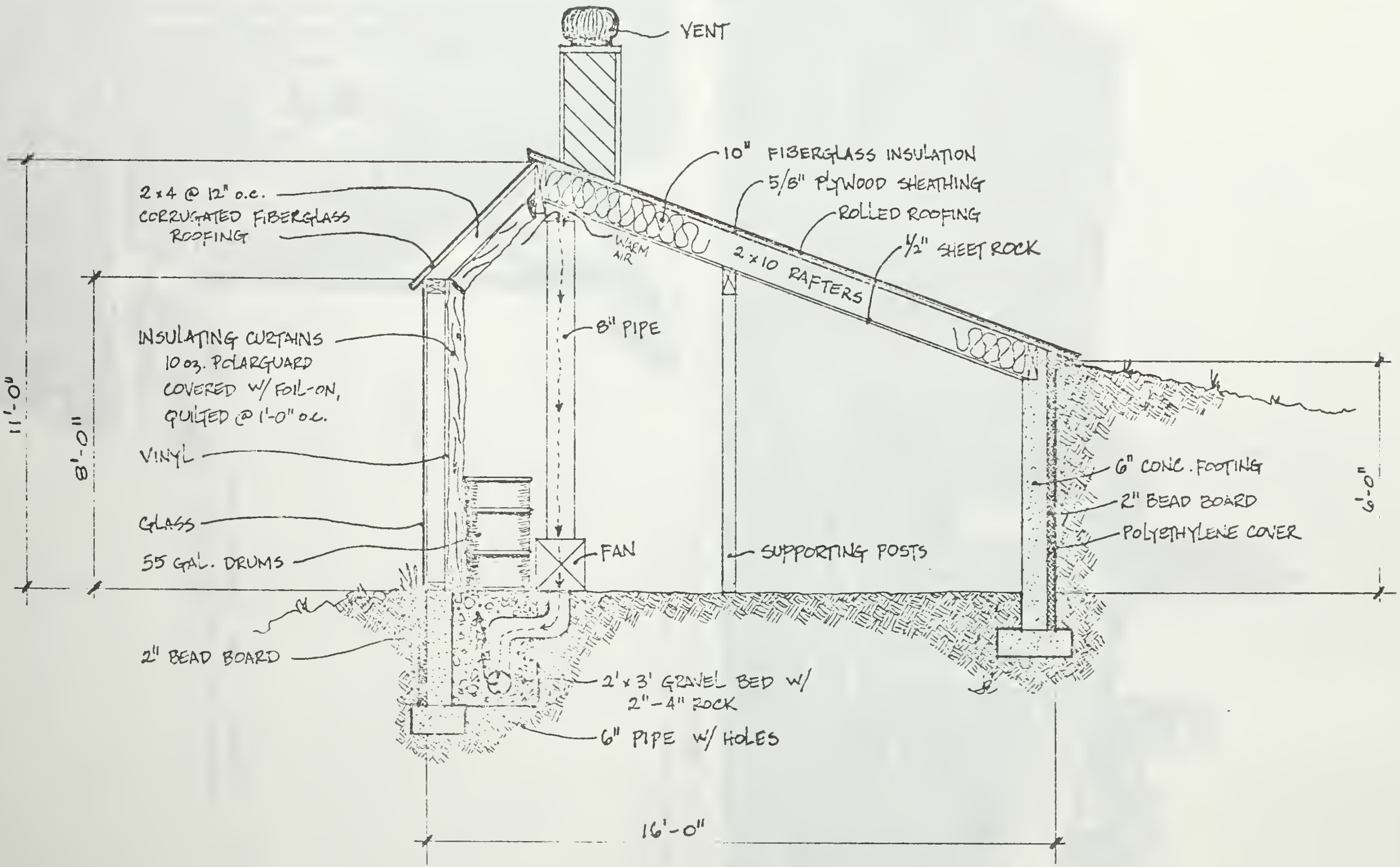


(a) Exterior View Showing Greenhouse Ventilating Towers and Support for Windmill



(b) Interior View Showing Duct Leading to Rock Storage

Figure 1: Photographs of Passive Solar Greenhouse



SECTION VIEW @ 1/4" = 1'-0"

Figure 2: Cross-sectional View of Passive, Earth Sheltered Greenhouse, Showing Construction and Active Rock Bin Storage

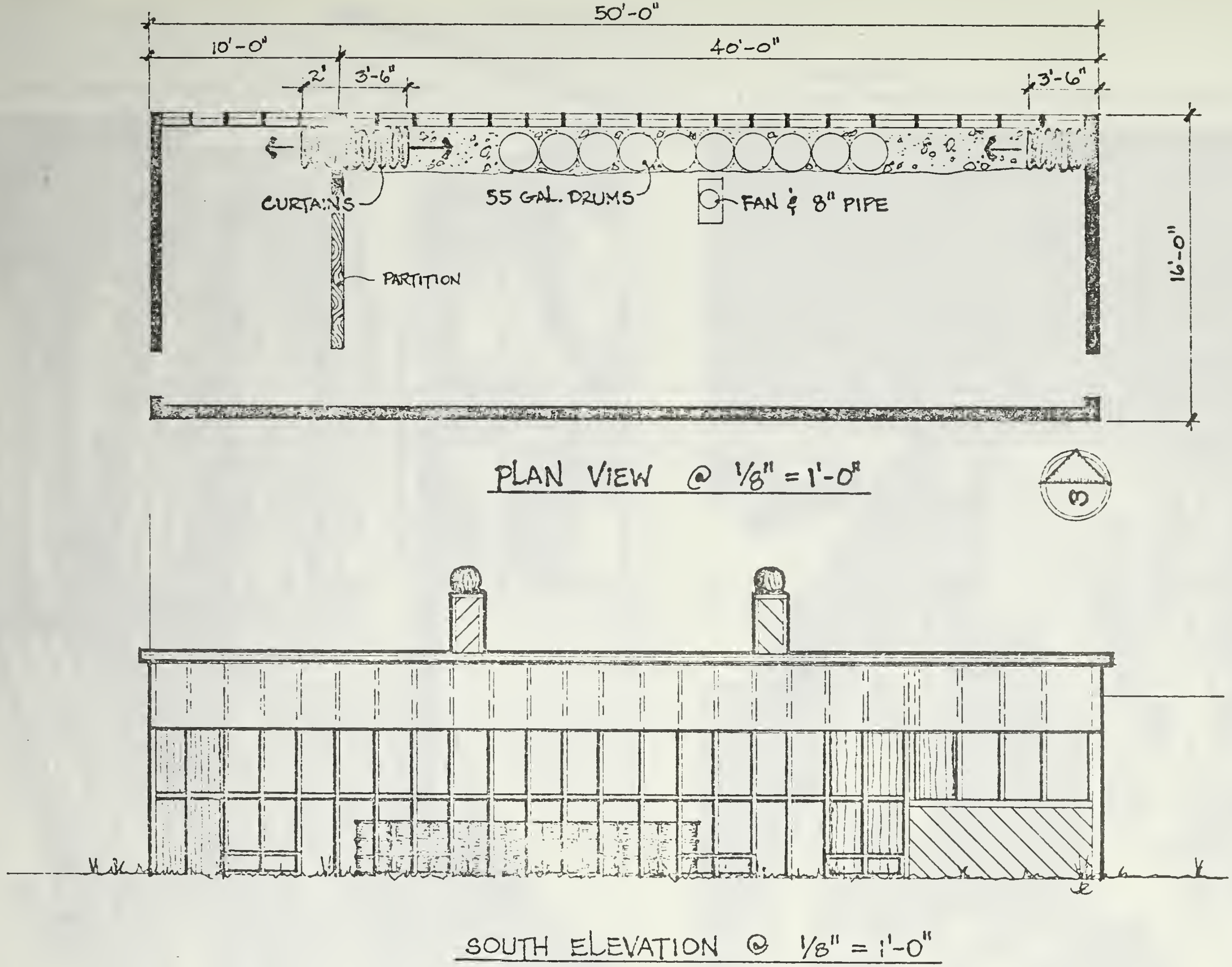
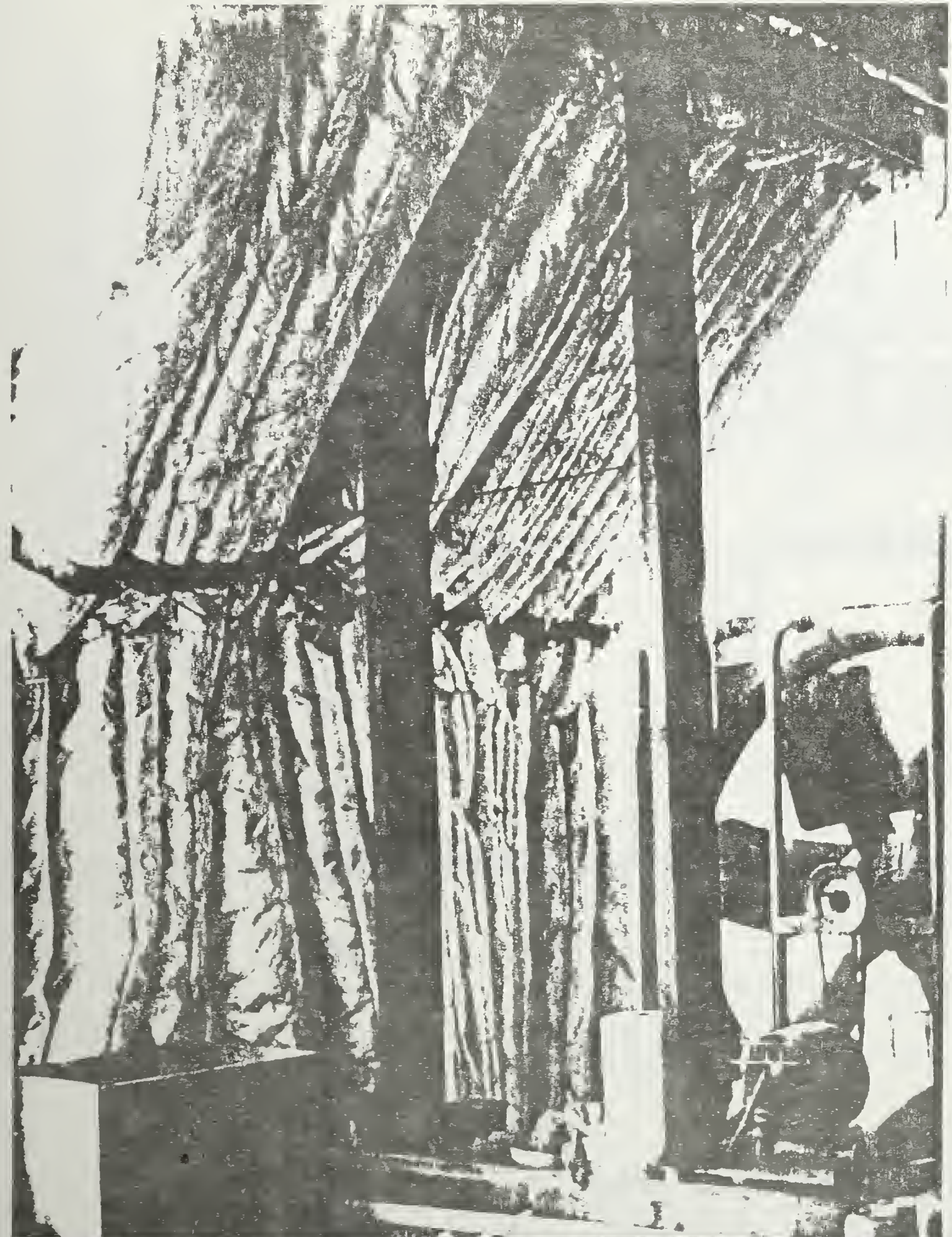
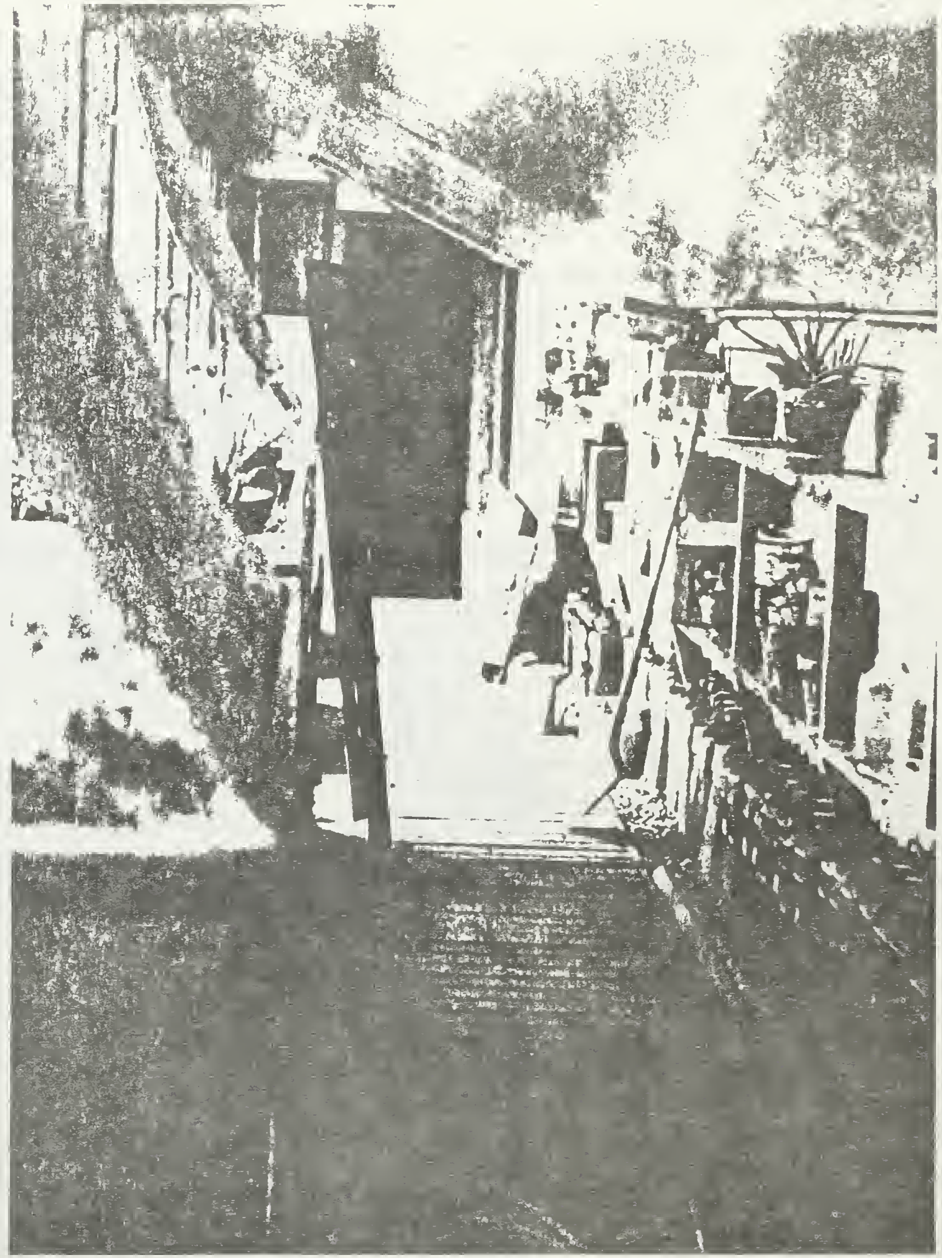


Figure 3: Plan View and Elevation View of Passive Solar Greenhouse



(a) Insulating Curtain in Open Position



(b) Rear Portion of Greenhouse Showing Storage Batteries

Figure 4: Interior of Passive Greenhouse

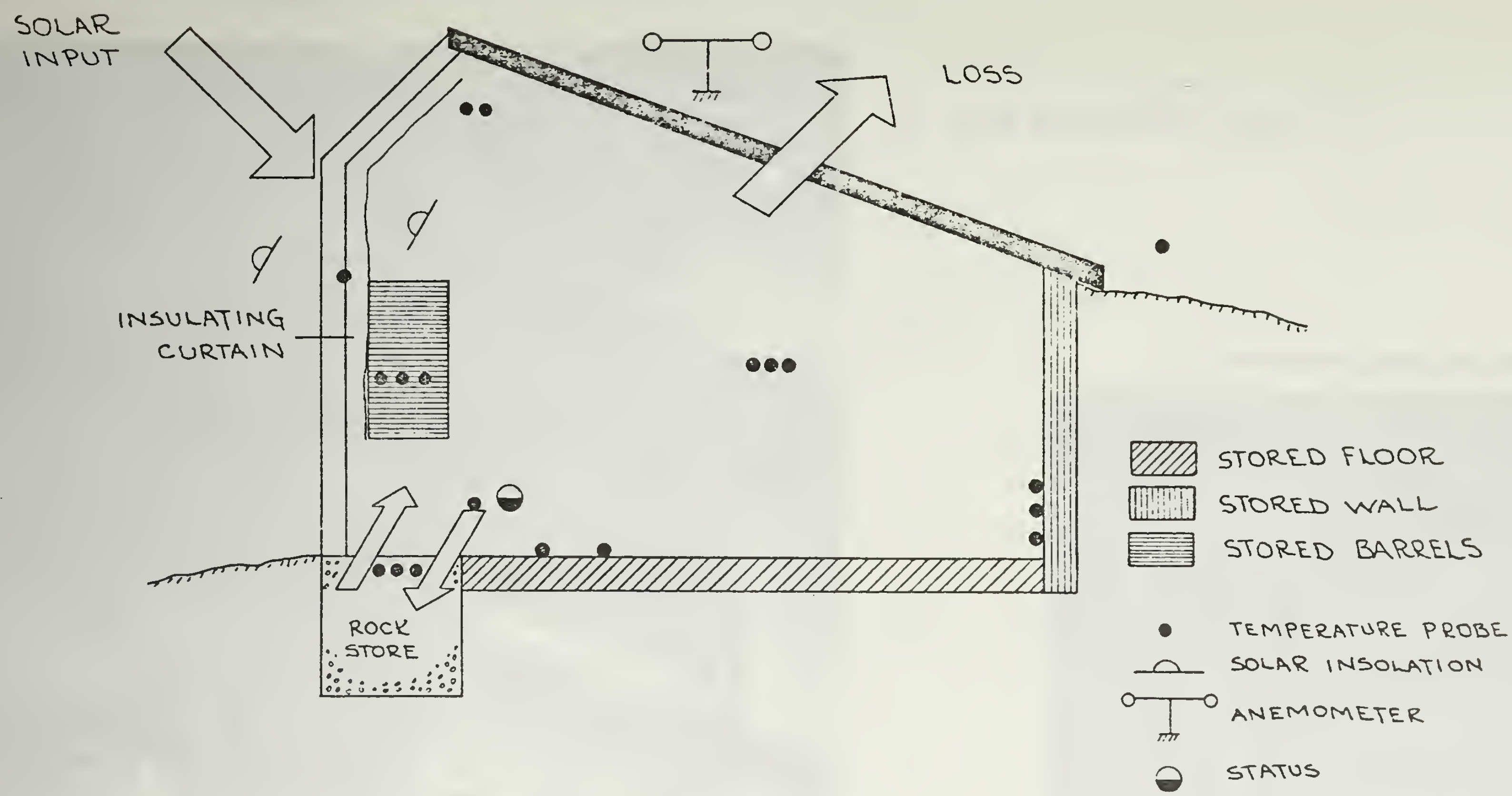
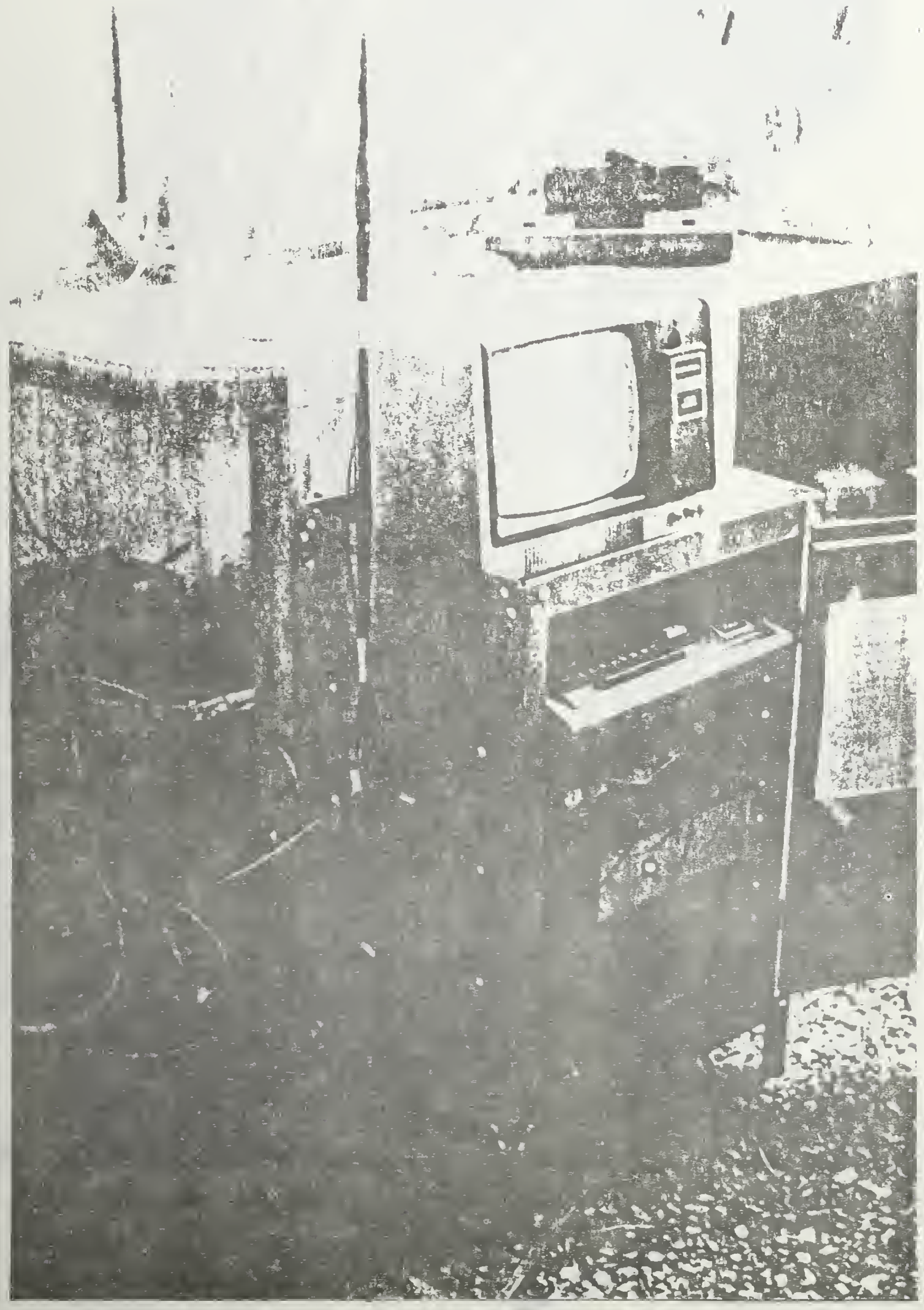
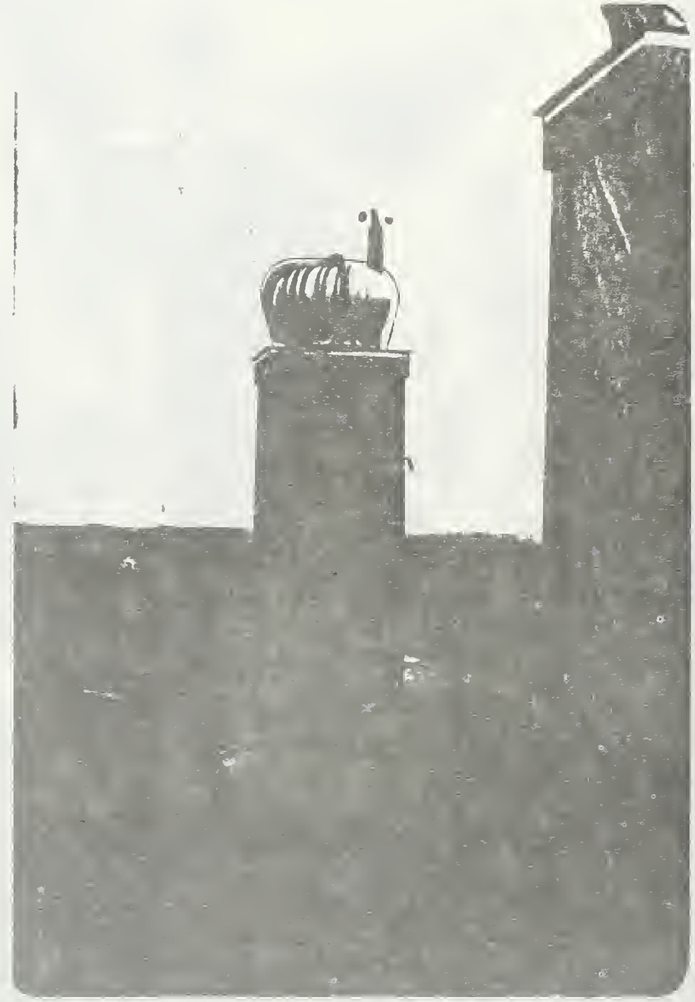


Figure 5: Schematic Drawing of Greenhouse Showing Transducer Arrangement and Conceptual Framework for Heat Balance Analysis

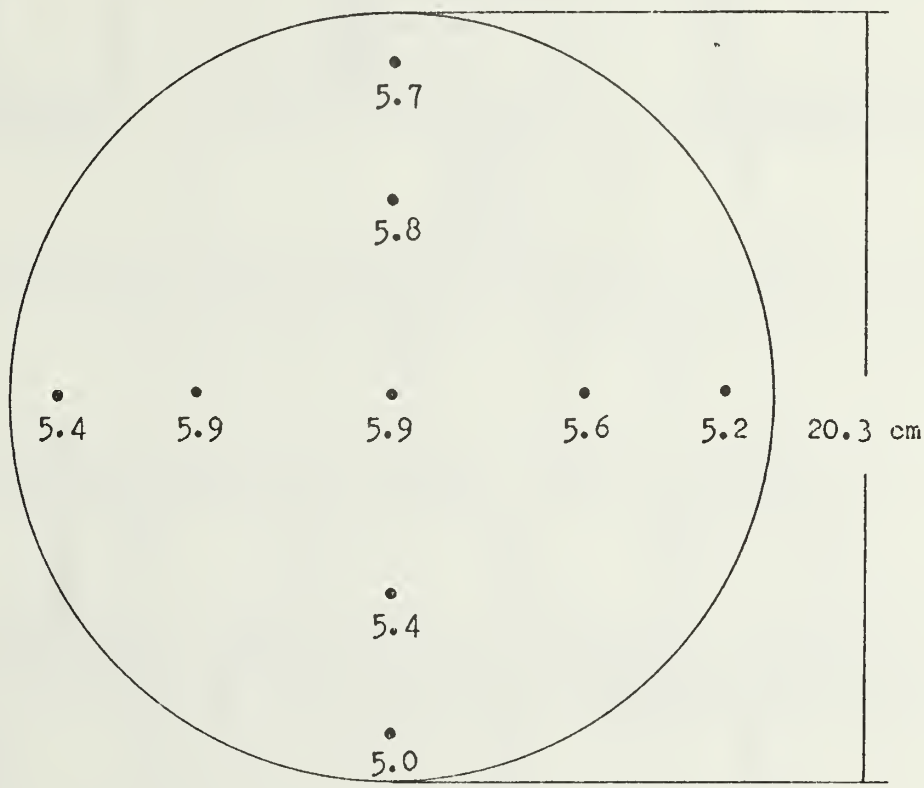


(a) Data Acquisition System



(b) Anemometer Mounted on Vent

Figure 6: Instrumentation for Passive Solar Greenhouse



Temperature = 10.67 °C

Average Velocity = 5.59 m/sec

Area = 0.0649 m^2

Flow Rate = 21.75 m^3/min

Figure 7: Map of Air Velocities in Duct Used to Charge Rock Bin Heat Storage

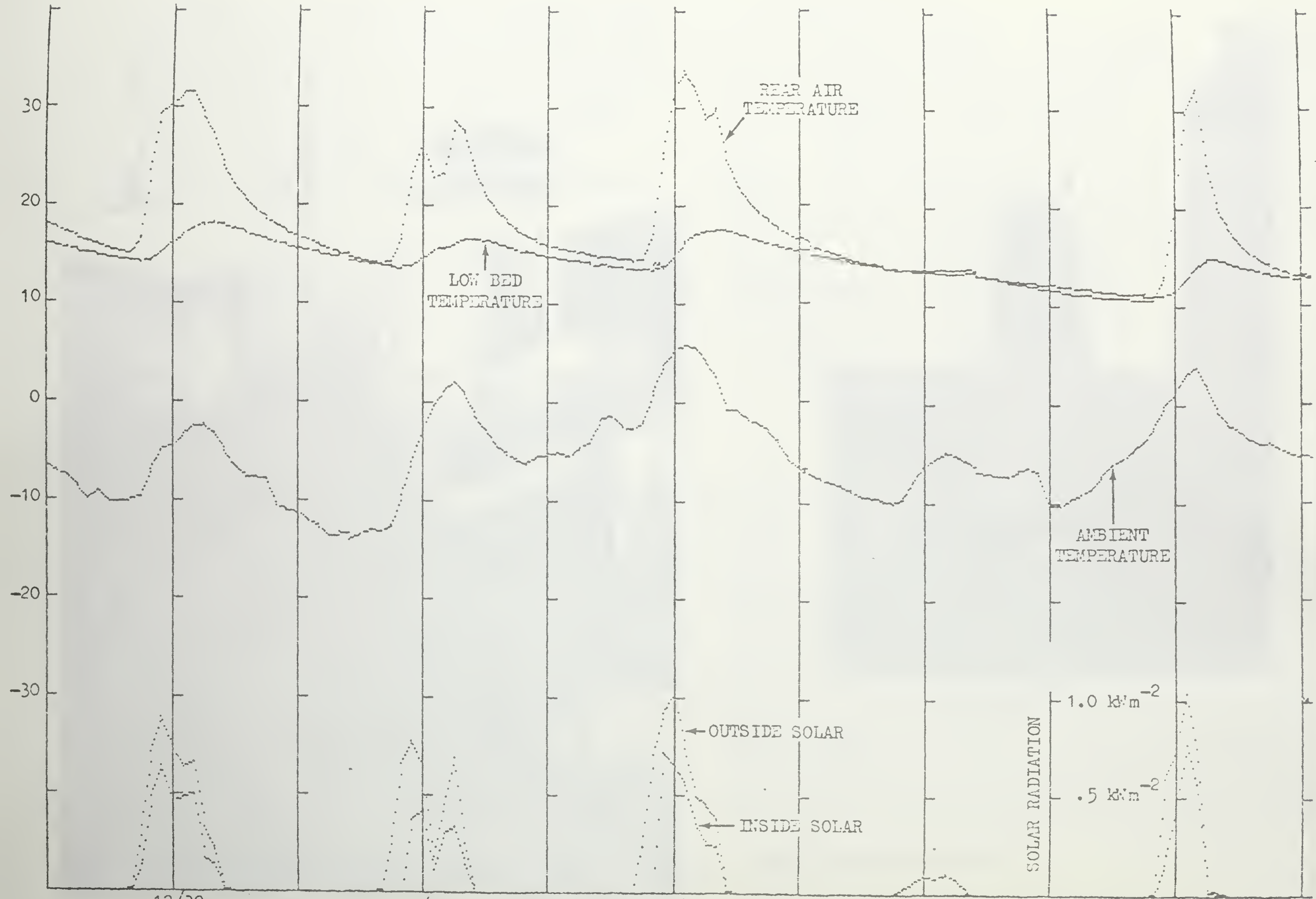


Figure 8: Graphical Presentation of Data for Five Days

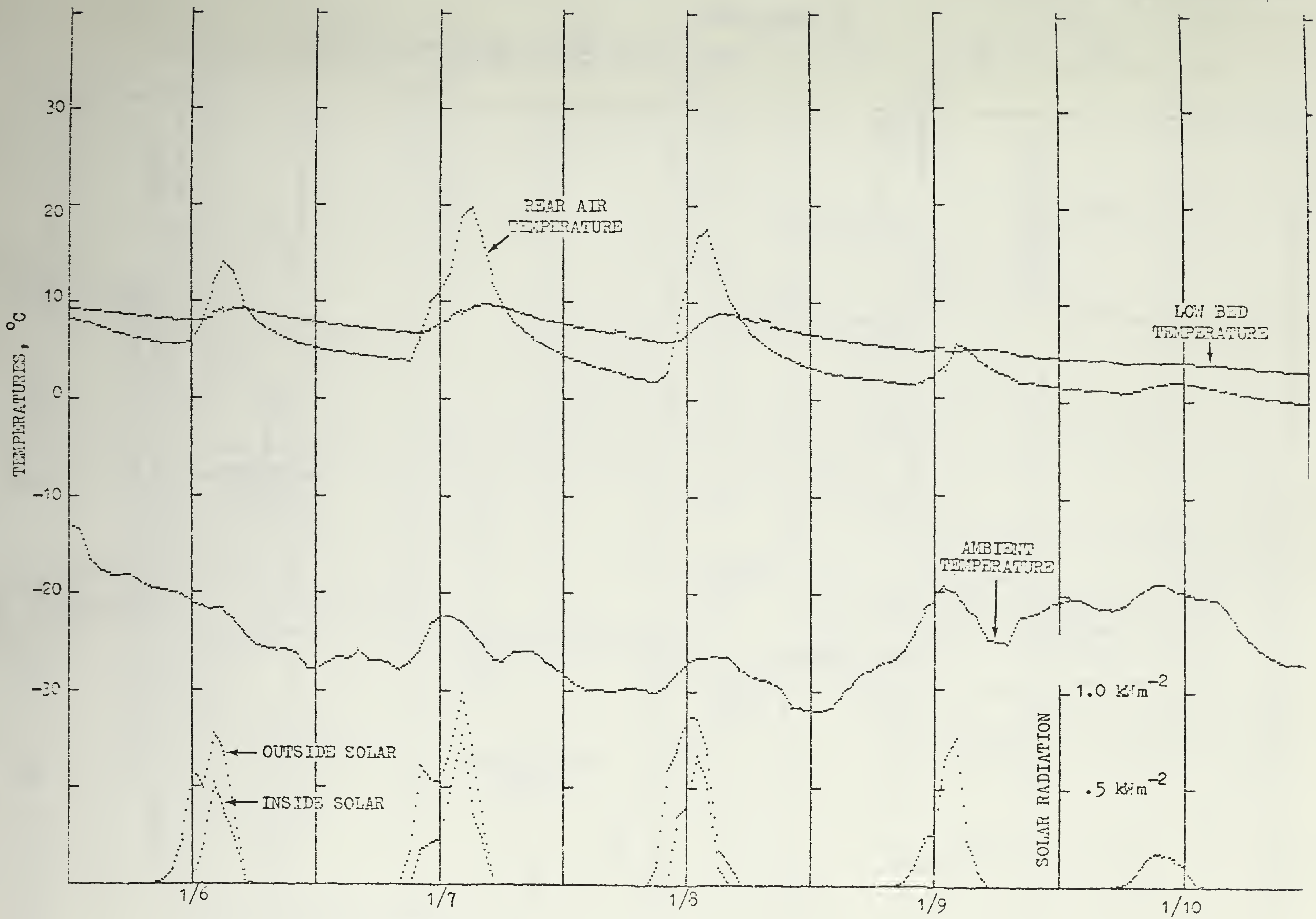


Figure 9: Graphical Presentation of Data for Five Days

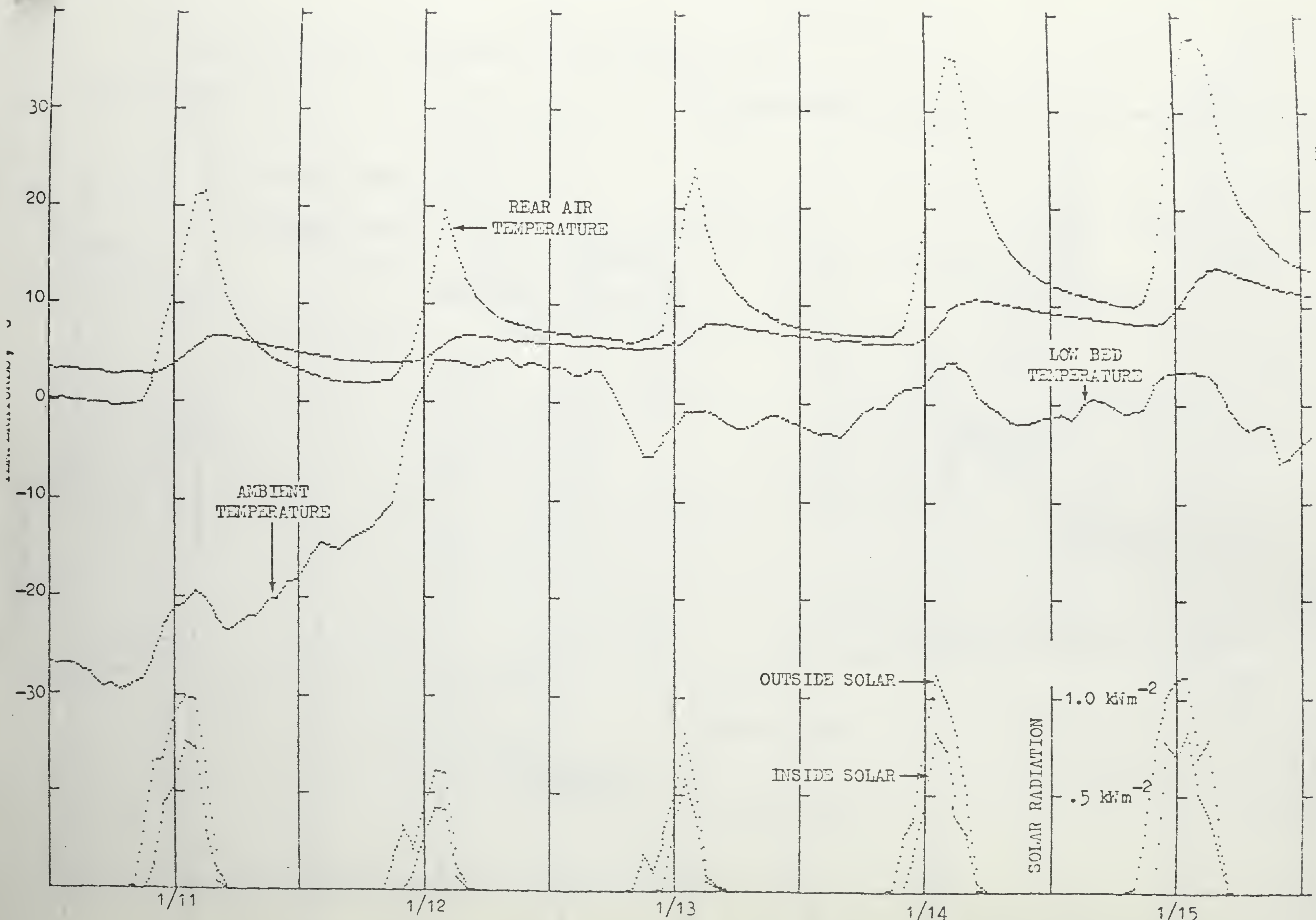


Figure 10: Graphical Presentation of Data for Five Days

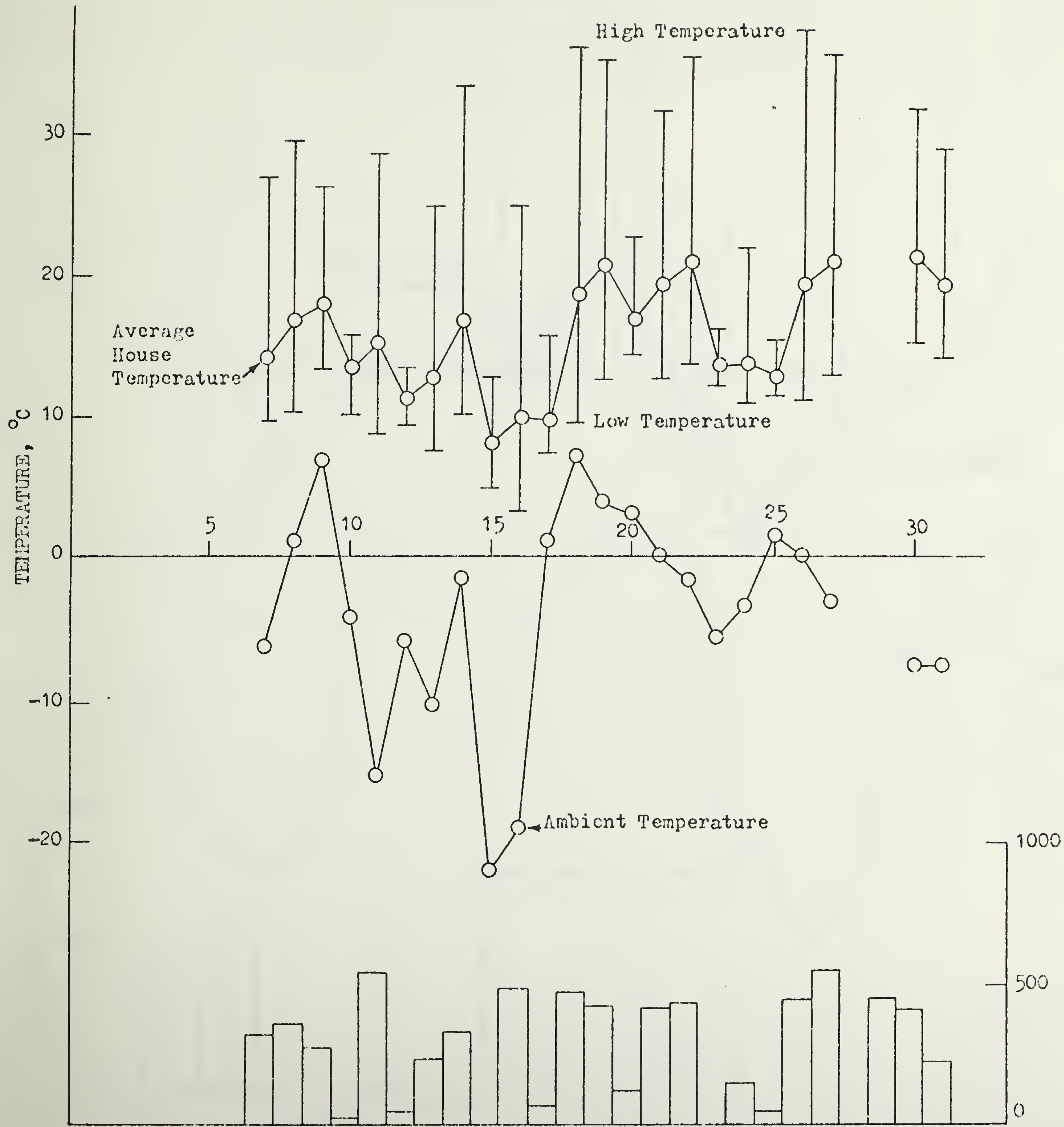


Figure 11: Graph of Inside Average Temperature and Range, Ambient Temperature and Solar Heat Input During December

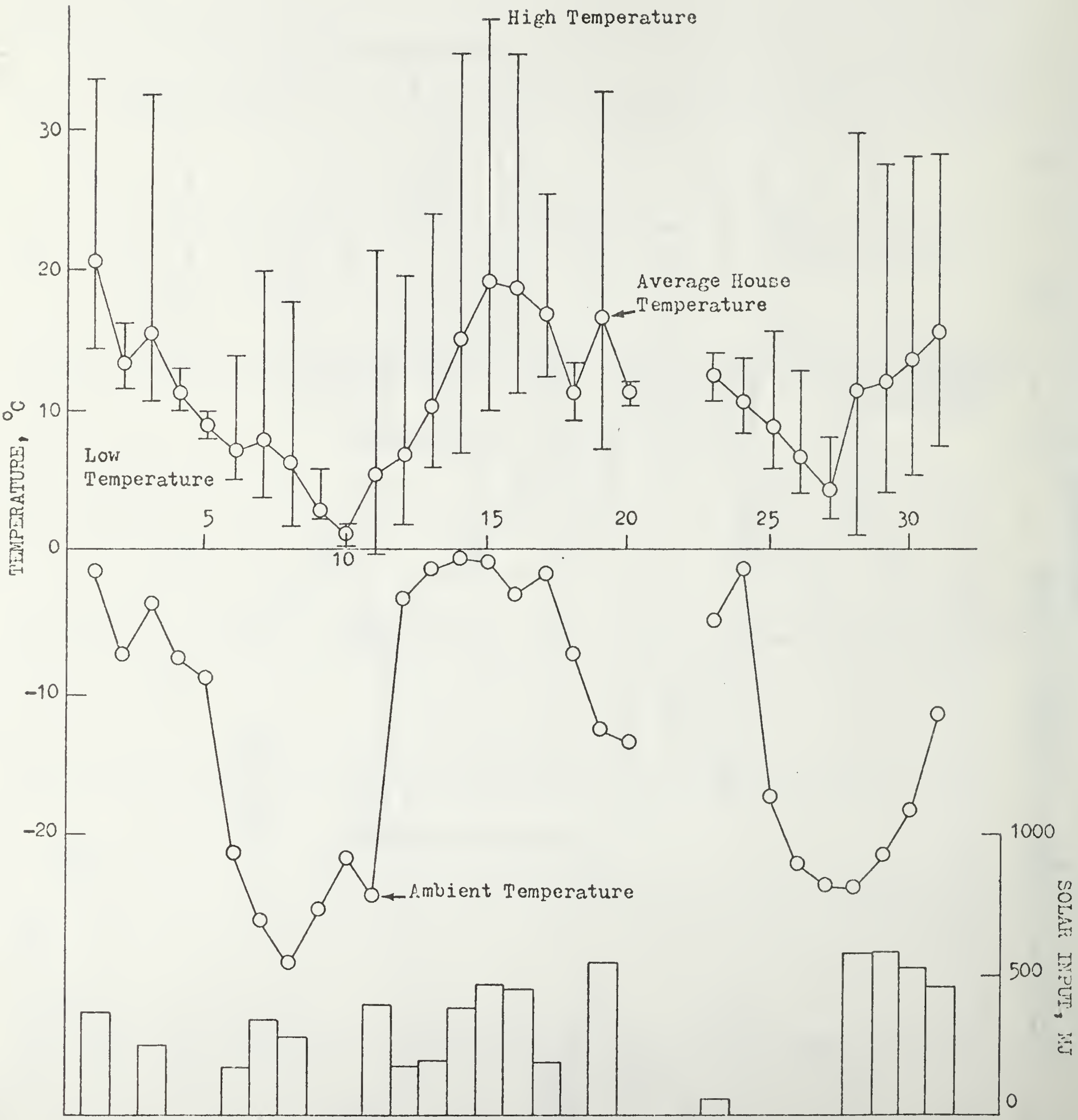


Figure 12: Graph of Inside Average Temperature and Range, Ambient Temperature and Solar Heat Input During January

APPENDIX I

TABLES OF HOURLY PERFORMANCE DATA FOR BROWN GREENHOUSE

```
500 REM *** CALCULATE HOURLY DATA ***
505 D(1)=V(2)*40*3.6\REM SOLAR INPUT
510 D(2)=1.59*(V(9)*V(4)-V(13))/2\REM ROCK STORAGE
520 D(3)=4.56*(A-V(9))\REM ROCK OUTPUT
530 D(4)=7.84*(B-V(7))\REM STORED BARREL
540 D(5)=11.38*(W-V(10))\REM STORED WALL
544 IF V(11)=V(16) THEN V(11)=V(11)+.01
545 D(20)=3.86*(V(16)-V(17))/(V(11)-V(16))\REM CURTAIN U-VALUE
547 IF D(1)>0 THEN D(20)=0
550 D(6)=36.1*(F-V(14))\REM STORED FLOOR
555 D(7)=D(1)+D(2)+D(3)+D(4)+D(5)+D(6)\REM SUMM INPUT
560 IFV(3)>.5THEND(8)=.86*(V(8)-V(17))ELSED(8)=.43*(V(8)-V(17))\REM CALLOSS
565 D(9)=V(17)\REM AMBT
570 D(10)=V(16)\REM INSULATING CURTAIN
575 D(11)=V(8)\REM REAR AIR TEMP
577 D(12)=V(11)\REM FRONT TEMP
580 D(13)=V(14)\REM LOW BED TEMP
582 D(14)=V(15)\REM HIGH BED TEMP
585 D(15)=V(9)\REM ROCK BED TEMP
587 D(16)=V(10)\REM BACK WALL TEMP
590 D(17)=V(7)\REM BARREL TEMP
592 D(18)=V(6)\REM WIND SPEED
595 B=V(7)\W=V(10)\F=V(14)\A=V(9)
598 D(19)=.014*V(6)↑3\REM WIND POWER
```

Equations Used to Calculate Hourly Data

DAILY PERFORMANCE SUMMARY FOR BROWN'S GREENHOUSE 12/ 7 R= 10

HR	SOLAR INPUT (MJ)	ROCK STORE (MJ)	ROCK OTPUT (MJ)	STORE BARRL (MJ)	STORE WALL (MJ)	STORE FLOOR (MJ)	SUN INPUT (MJ)	CALC LOSS (MJ)	AMBT TEMP (C)	INSL CURT (C)	REAR TEMP (C)	FRONT TEMP (C)	LOW BED (C)	HIGH BED (C)	ROCK BED (C)	BACK WALL (C)	BARRL TEMP (C)	WIND SPEED (M/S)	WIND POWER (MJ)	CURT U-VAL (W/M2 C)
1	.0	.0	.7	.4	.6	3.2	4.9	5.0	-1.0	.7	10.5	7.7	9.6	9.1	6.2	9.2	8.6	10.9	17.9	1.0
2	.0	.0	.8	.7	1.0	2.5	5.1	5.2	-1.6	.2	10.4	7.5	9.5	9.0	6.1	9.1	8.5	10.2	16.7	1.0
3	.0	.0	.9	.6	.7	2.5	4.7	5.4	-2.4	-.3	10.2	7.4	9.4	8.9	5.9	9.1	8.4	10.4	15.7	1.0
4	.0	.0	1.0	.5	.6	3.6	5.7	5.8	-3.4	-.9	10.1	7.2	9.3	8.8	5.6	9.0	8.4	8.7	9.3	1.2
5	.0	.0	1.0	.5	1.0	2.5	5.1	6.0	-4.1	-1.5	9.9	7.1	9.3	8.6	5.4	8.9	8.3	7.7	6.6	1.2
6	.0	.0	1.0	.6	.7	2.9	5.2	6.1	-4.3	-1.6	9.8	7.0	9.2	8.5	5.2	8.9	8.2	6.2	3.4	1.2
7	.0	.0	.6	.5	.5	2.5	4.1	6.0	-4.2	-1.3	9.8	6.9	9.1	8.4	5.1	8.9	8.1	5.3	2.1	1.4
8	.0	.0	.7	.7	.8	3.2	5.4	6.4	-5.3	-1.5	9.7	6.8	9.0	8.3	4.9	8.8	8.1	5.7	2.6	1.6
9	.0	.0	.2	.4	.3	1.4	2.4	6.6	-5.8	1.6	9.6	6.8	9.0	8.2	4.9	8.7	8.0	6.3	3.5	5.4
10	.0	.0	-.7	.0	.7	3.2	3.2	6.9	-6.4	3.6	9.7	6.9	8.9	8.1	5.0	8.7	8.0	6.5	3.9	11.8
11	17.3	.0	-1.4	-.2	-.1	.0	15.6	14.6	-6.2	7.7	10.7	9.0	8.9	8.2	5.3	8.7	8.0	5.2	2.0	.0
12	67.7	.0	-2.6	-3.1	-5.5	-9.7	47.4	19.9	-6.0	23.8	17.1	17.7	9.2	9.4	5.7	9.2	8.6	3.4	.6	.0
13	106.5	-1.3	-2.6	-5.5	-14.3	-28.9	56.6	25.8	-5.3	36.7	24.7	30.9	10.0	12.2	6.3	10.4	9.1	.5	.0	.0
14	82.1	-16.0	-5.9	-4.6	-11.3	-39.6	5.9	26.9	-4.6	37.5	26.7	30.9	11.0	15.9	7.6	11.4	9.6	1.2	.0	.0
15	43.3	-13.4	-7.9	-3.9	1.3	-23.5	-12.2	26.5	-5.6	36.0	25.9	28.4	11.8	16.6	9.3	11.3	10.1	.6	.0	.0
16	11.5	-6.7	-5.3	-1.8	1.6	-15.9	-16.6	24.7	-6.7	20.0	21.4	20.0	12.3	16.7	10.5	11.2	10.4	2.5	.2	.0
17	.0	.0	2.9	.6	1.6	-1.4	3.7	11.4	-8.4	3.0	16.1	15.8	12.3	15.7	9.9	11.0	10.3	2.0	.1	3.4
18	.0	.0	5.8	.9	1.6	6.9	15.1	10.9	-9.2	-.7	16.1	13.7	12.1	14.7	8.6	10.9	10.2	2.4	.2	2.3
19	.0	.0	4.5	.9	1.6	7.9	15.0	10.8	-10.5	-2.2	14.6	12.1	11.9	14.0	7.6	10.7	10.1	3.1	.4	2.3
20	.0	.0	3.8	.5	1.6	8.7	14.8	10.8	-11.5	-3.1	13.4	11.1	11.7	13.3	6.8	10.6	10.0	1.3	.0	2.3
21	.0	.0	2.9	.8	1.4	8.7	13.7	10.3	-11.6	-3.3	12.9	10.3	11.4	12.8	6.1	10.5	9.9	.9	.0	2.2
22	.0	.0	2.2	.8	1.3	8.7	12.9	9.9	-10.6	-3.4	12.4	9.8	11.2	12.3	5.7	10.4	9.9	1.3	.0	2.1
23	.0	.0	1.6	.9	1.3	7.9	11.7	9.4	-9.9	-3.3	11.9	9.3	11.6	12.0	5.3	10.3	9.6	3.3	.5	2.0
0	.0	.0	1.2	.9	1.1	7.2	10.5	8.7	-8.7	-3.0	11.5	8.9	10.8	11.6	5.0	10.2	9.5	3.9	.9	1.9
	325.4	-37.5	6.2	-7.0	-10.1	-39.7	237.4	279.4	-6.3	5.9	14.0	12.6	10.3	11.3	6.4	9.8	9.1	4.5	84.2	

APPENDIX II

DATA ACQUISITION SYSTEM

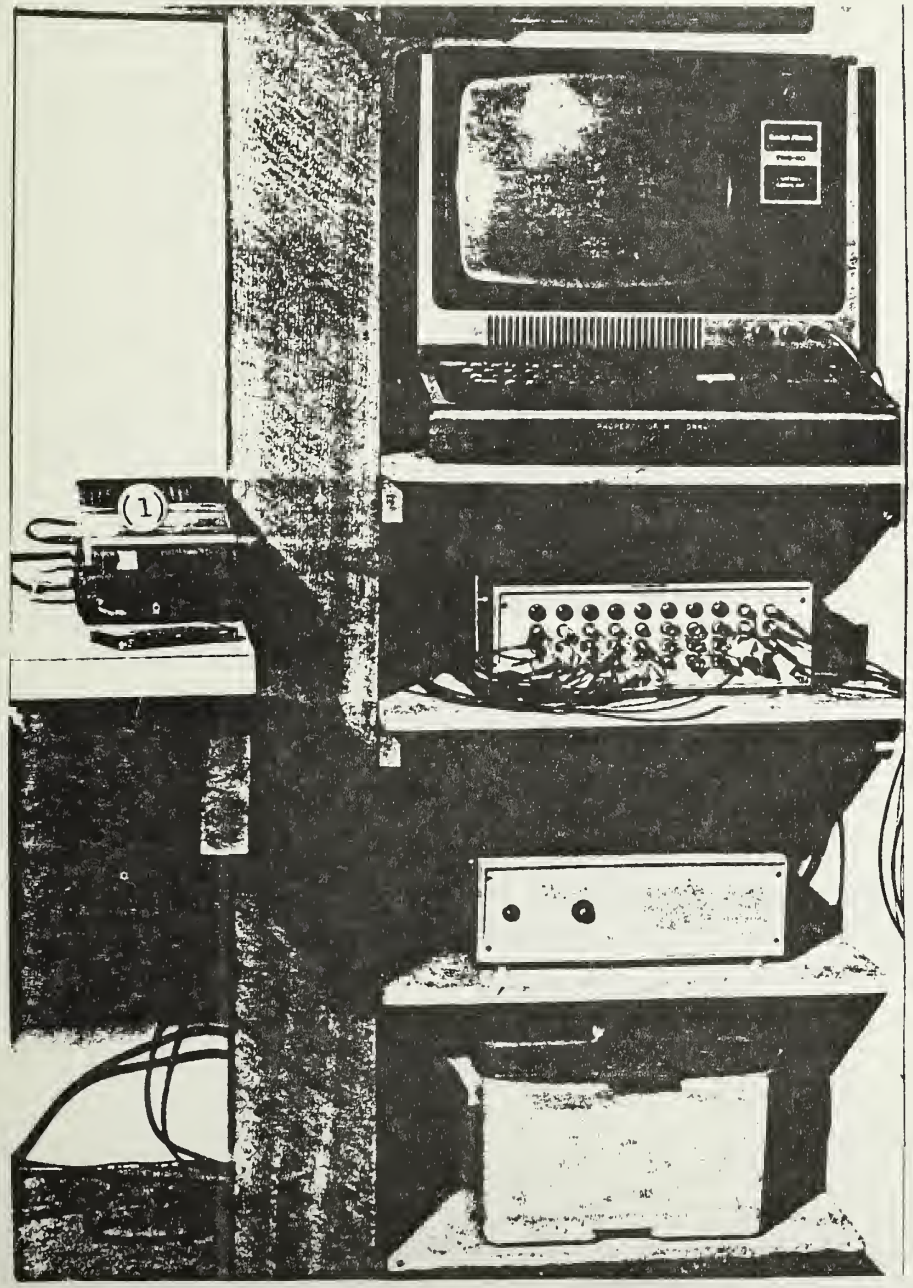
A low cost data acquisition system was developed for solar performance monitoring and is pictured in Figure 1 on the following page. The heart of the system is a Radio Shack TRS-80 computer having a 4K memory. This system has the capability of 40 input channels and is controlled by a Level II BASIC program which allows the user to structure data sampling and processing procedures. Calibration constants, error checks, scan rate, data averaging, printing, etc., can be manipulated using this program capability. A real time clock within the A/D converter chassis is used to time the data output on the cassette. Scanning at an average rate of 40 channels per five seconds, the data is averaged at the end of each hour. This data is then written onto the cassette recorder for processing at a later time.

Temperatures were measured using AD-590 transducers made by Analog Devices. A BASIC computer program was used with the data acquisition system to calibrate the probes against a precision thermometer. The absolute accuracy of the temperatures measured is better than 0.5°C (1°F), while the accuracy of small temperature differences is 0.1°C (0.18°F).

Total solar radiation on the collector surface was measured using a silicon cell pyranometer. The device was manufactured by the contractor and is mounted in the plane of the solar collector. The device has been referenced to NOAA Standards with an estimated overall accuracy of 5%.

Electric power is measured using clamp-on ammeters calibrated on-site against the utility kWh meter. The status of motors, dampers, curtains and fans is determined using appropriate relays, microswitches or mercury switches.

Flow in liquid systems is measured using Hersey MVR-30 turbine meters which have been interfaced to the DAS. Flow in air systems is mapped using a hot-wire anemometer for a one-time measurement to characterize the flow. Status switches and software combine the one-time measurements to calculate appropriate heat flow quantities.



— Video display of current data scan: 40 channels, time, date

— Keyboard for controlling system

(1) Cassette for storing data and programs

— 40 channels analog input, A/D conversion (12 bit), real time clock

— Power supply for computer and A/D interface

— 12V battery: powers system up to 5 hours in the event of a power shortage

Figure 1: Computer-Based Data Acquisition System

THERMAL PERFORMANCE

OF THE KILBY SOLAR HOUSE

by

Charless W. Fowlkes

FOWLKES ENGINEERING
31 Gardner Park Drive
Bozeman, MT 59715

for

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
RENEWABLE ALTERNATIVE ENERGY SOURCES PROGRAM

Grant #RAE-145-800

NOTE ON UNITS

The test results in this report are given in metric or SI units. This convention corresponds to current professional practice and is in accord with the recommendations of the International Solar Energy Society and most technical journals.

Most readers are familiar with the Celsius or Centigrade temperature scale (^{o}C) and with power measured in kilowatts (kW). The metric unit of energy is the Joule (J). Most energy quantities in this report are expressed in megajoules (MJ) which is 10^6 joules or a million joules (1,000 BTU = 1 kBTU = 1.05 MJ). Since one MJ is about one thousand BTU's, a furnace with a rating of 100 thousand BTU/hour would be rated at about 100 MJ/hour. This approximate conversion will be useful to the reader accustomed to thinking in thousands of BTU.

Other abbreviations included in this report are: l = liters, m = meters, m^2 = square meters and kWh = kilowatt hours.

ABSTRACT

Active liquid, tracking, concentrating solar collectors were retrofit to a residence owned by William Kilby and located in Great Falls, Montana.

The collectors have an aperture area of 29.7 m^2 and the system was designed to supply heat through a baseboard hot-water heating system to an existing house having a floor area of 192.5 m^2. The tracking collectors were chosen for this system in order to provide the higher temperatures needed by the heat distribution system in the house. The collectors are located on a frame above the garage in the back yard of the house.

During the monitoring period, the solar collectors provided 11% of the heat requirements of the house. The auxiliary gas furnace provided 55% and electrical dissipation provided 34%. The overall efficiency of the collectors was about half the expected efficiency. The outlet temperature of the collectors and the temperature of the hot water in the storage system was often too low to be used by the house. As a result, only a small percentage of the solar heat collected was delivered to the house, leading to the low overall solar fraction. The complexity of the system has resulted in numerous failures and produced an overall coefficient of performance of the collector system of 3.4. The specifications of the system are given in the table below:

<u>SOLAR COLLECTOR</u>

Type: Active liquid, tracking
Manufacturer: Northrup Corp.
Aperture Area: 29.7 m^2
Glazing: Single, plastic
Absorber: Copper
Fluid: 50/50 ethylene glycol/water
Thermal Capacity: .0034 $MJ l^{-1}\ ^oC^{-1}$
Flow Rate: 42.9 $l\ min^{-1}$
Tilt: 45°
Azimuth: 180°

<u>STORAGE SYSTEM</u>

Material: Water
Volume: 3.8 m^3
Thermal Mass: 15.9 $MJ\ ^oC^{-1}$

<u>AUXILIARY HEAT</u>

Type: Boiler
Fuel: Natural gas

<u>BUILDING</u>

Type: Brick
Floor Area: 192.5 m^2
Calc. Loss Factor: 0.91 $MJhr^{-1}\ ^oC^{-1}$

TABLE OF CONTENTS

TABLES

FIGURES

1.0 INTRODUCTION

This solar system was designed and built by William Kilby. The solar system was retrofit to an existing house located in a suburban area in Great Falls, Montana. This system has been in operation about two years. The system has experienced numerous failures and has undergone a number of changes during the course of its development. The author of this report acknowledges the interest and generous assistance of Mr. Kilby while monitoring this system.

2.0 DESCRIPTION OF THE HOUSE

The Kilby house is shown in Figure 1 and the solar collector array and its supporting framework are shown in Figure 2. A floor plan of the Kilby house is given in Figure 3. This is a single story house built over a full basement, is well insulated and in good condition. The calculated heat load of the Kilby house is shown in Table 1. The overall heat load for this house is 0.91 $MJhr^{-1}$. The collectors have a relatively good exposure to the sun as shown by the shading diagram in Figure 4. Some trees to the east of the collector array provide shading during fall and spring until about 10:00 in the morning. In the middle of the winter, tall trees located along the street in front of the house provide partial shading of the collectors until about 11:30 in the morning.

3.0 DESCRIPTION OF THE SOLAR SYSTEM

The solar collectors, the associated mechanical equipment and the heat storage are located in the garage about 15 m from the house, Figure 5. Hot water from the solar system is circulated to the house through underground pipes. Figure 6 shows a schematic of the solar system. A bank of 32 tracking Northrup collectors collect solar heat in a liquid solution of 50% water and 50% ethylene glycol. This solution is circulated by a collector pump through a heat exchanger. Water circulates through the other side of the heat exchanger. This solar heated water can be circulated (a) directly into the house, (b) into solar

storage and/or (c)into the domestic hot water preheat tank. The differential thermostat which controls the collector pump also controls the circulation pump in the storage loop.

The furnace has a thermostatic valve which is controlled by the temperature of the solar storage. If the temperature of the storage is high enough and the house thermostat calls for heat, the house circulation pump turns on and draws solar heated water from the storage tank and circulates it through the baseboard units, Figure 6. Figure 7 shows the auxiliary gas boiler and circulation pump. Figure 8 shows the domestic hot water preheat tank and Figure 9 shows the solar collector to storage loop heat exchanger.

4.0 INSTRUMENTATION

The data acquisition system is described in Appendix II. The location of measurement probes is shown in the schematic in Figure 6. The collector loop contains a flow meter and a temperature probe measuring the outlet collector fluid temperature at the heat exchanger and the return temperature to the solar collectors. The collector circulation pump is instrumented with a status relay.

Solar radiation was measured with a fixed radiometer in the plane of the collector array. A second solar radiation transducer was attached to the face of one of the tracking collectors to measure the actual radiation in the plane of the tracking collector as it follows the sun.

The solar storage loop has three flow meters: One flow meter measures any flow through the heat exchanger, a second flow meter measures flow through the house circuit, and the third flow meter measures the flow through the domestic hot water preheat tank. A fifth flow meter was installed in the cold water inlet to the domestic hot water preheat tank to measure hot water usage.

In the storage loop, temperature transducers are located at the inlet and the outlet of the heat exchanger, at the inlet to solar storage, at the inlet and outlet of the domestic hot water preheat tank, and at the inlet and outlet to the house heat distribution system. Temperatures

are also measured in the domestic hot water circuit. One probe measures the cold water inlet to the preheat tank, a second probe the outlet from the preheat tank, a third and fourth probe measure the inlet and outlet temperatures of the domestic hot water auxiliary heater, located in the house. The solar storage was instrumented with three probes taped to the surfaces of the storage tanks and insulated. These probes measure the average storage temperature.

Figures 10 and 11 document the locations of the probes in this system as well as calculated parameters stored in the computer system. All of the flow meters were connected directly to the data acquisition system, with the exception of the flow meter in the collector loop. This meter was read periodically by Mr. Kilby. These readings, in conjunction with the total hours that the pump was on in the collector circuit, allowed us to calculate an average flow rate in the collector loop. Table 2 reproduces the log of these flow meter readings. The average collector flow was 42.9 $l\ min^{-1}$ (679.7 gal/hr).

The computer based data acquisition system was programmed to take the readings of the flow meters during each scan and multiply them by the appropriate temperature differences and specific heats to calculate the heat added or taken from each element in the system. The collector efficiency was also calculated on line. These calculated values are discussed in detail in Figures 10 and 11.

5.0 DATA ANALYSIS

All the hourly raw data was compressed and summarized in the format of an Hourly Performance Summary shown in Table 3. In this Table, the first column shows the solar radiation ($kW{-}m^{-2}$) in the plane of the collector array as measured by the tracking transducer. The second column shows the total solar radiation striking the collector array and the third column lists the net heat output of the collector array (calculated using the flow rate and temperature difference across the heat exchanger on the collector side).

The next three columns show the distribution of the solar heat that was collected. Solar heat can go into the domestic hot water heat

exchanger (SOLAR DHWX), into the main solar storage (SOLAR STORE) or directly into the house (SOLAR HOUSE). Auxiliary heat from the gas boiler going into the house is listed in the next column (AUX HOUSE).

The energy inputs into the house consisted of SOLAR HOUSE, AUX HOUSE and average electrical dissipation into the house (from utility meter readings). When added together, these inputs form the column labeled SUM INPUT, which can be compared to the next column, HOUSE LOAD. HOUSE LOAD is calculated from the house conductive load factor multiplied by the current temperature difference between the inside and the outside of the house.

The next four columns show the temperature of the mechanical room, the temperature of the heat storage tanks, the ambient air temperature, and the house air temperature, in degrees Celsius. The next column is labeled DELTA STORE. This quantity is computed by taking the hourly temperature difference of the heat storage and multiplying it by the thermal mass of the entire storage system. The next column, STORAGE LOSS, was calculated using an experimentally determined overall heat loss factor multiplied by the mechanical room temperature minus average storage temperature. The final column is labeled AUXILIARY POWER and is the electrical energy used to run the pumps and equipment necessary for operation of the solar system.

Looking at Table 3, we can see that some solar radiation is falling on the collector between 8:00 and 9:00 and that the collectors turn on and begin to deliver heat between 9:00 and 10:00 a.m. The collectors operate continuously until about an hour before sunset when the circulation pump turns off. Looking at the SOLAR HOUSE and AUX HOUSE columns, we see that until 8:00 a.m., heat was being supplied to the house entirely by the auxiliary furnace. At this point, the house begins to use solar heat. About an hour after sundown the system switches back to the auxiliary heat mode.

The bottom line of this Table shows the daily totals of the energy quantities and the daily averages of all temperatures. During this day,

a total of 931 MJ of solar radiation was available to the collectors. A total of 278 MJ was collected by the system and delivered to the heat exchanger. Solar heat totaling 225 MJ was delivered to the solar storage system, of which about 10% was lost during the day. A total of 54 MJ of solar heat was delivered to the house during this 24-hour period, and 171 MJ of auxiliary energy was used in the house. Hourly data for the entire monitoring project is listed in Appendix I in this format.

A monthly summary of the daily totals and averages for the entire monitoring period are given in Tables 4, 5 and 6. The information in these Tables give a picture of the performance of this system at a moderate level of detail. Notice that after the first week of operation, zeroes appear in the column under solar domestic hot water exchanger. This is because the tank developed a leak and was removed from the system. Late in March there are also many zeroes in the collector output column. These zeroes appear because the system was turned off due to leaks. Table 7 is an overview of some of the system failures during the monitoring period, and is a helpful aid to understanding the data tables.

This data is further summarized in Table 8, which gives monthly totals and overall totals for the entire monitoring period. Table 8 shows that during the monitoring period 11% of the heat required by the house was supplied by the solar system. Electrical dissipation accounted for 34% and the auxiliary natural gas furnace provided 55%. During the monitoring period, the collector array intercepted a total of about 42,000 MJ and delivered about 11,000 MJ to the heat exchanger, for an average overall efficiency of 26%. Of the 11,000 MJ collected, only 2,800 were actually delivered as useful heat to the house. The system required 816 MJ of electric energy for operation, giving an overall coefficient of performance of 3.4.

6.0 GRAPHICAL PRESENTATION OF RESULTS

Figures 12 and 13 contain graphs of a portion of the hourly data

covering a period of 10 days. These curves show solar radiation intercepted by both the stationary radiometer and the tracking radiometer. The ambient temperature and the temperature of the solar storage is also graphed. The top two curves on these graphs show the status of the solar collector pump and the mode of the house heating system. (When the auxiliary heating system is in the solar mode it can withdraw heat from solar storage.)

The variations of the temperature of the solar storage reflect periods when the solar collectors are adding heat to the storage as well as periods when the house is extracting heat from the storage. Note the relation of the bumps and dips in storage temperature to the status of the collector pump and the status of the house mode. These hourly graphs, in conjunction with the Tables of Hourly Data in Appendix I, depict the dynamics of the workings of this solar system in great detail.

Figures 14 and 15 are graphical presentations of daily summary data. The daily average temperatures of the house, the ambient air and the solar storage are shown. The bottom part of these graphs is a bar chart showing the solar radiation available, the portion of the solar radiation collected, and the portion of the solar heat delivered to the house. These graphs should be studied in conjunction with the complete data given in Tables 4 and 6. One point noted from these graphs is that the temperature of the storage during cold weather averages around 40°F or below. This temperature is well below the 70°F temperatures needed by the baseboard heating system in the house.

7.0 COMPARISON OF SYSTEM PERFORMANCE TO F-CHART ANALYSIS

Table 9 shows a comparison of solar radiation measured at the Kilby site and at the *SIMM Station located in Great Falls at C.M. Russell high school. This radiation is measured on a 60° tilt. When transformed onto a 45° tilt (the slope of the Kilby collectors), the SIMM values agree quite closely with the values measured at the Kilby site.

Solar radiation data from the SIMM data base was used in conjunction

*Solar Insolation Measurement Montana (another DNR&C program)

with long-term temperature data as input to an f-chart analysis for this system. The collector efficiency data for the Northrup collectors was input into this design analysis. While the f-chart analysis is not specifically tailored for these tracking collectors, it is presented here to provide some guidelines on performance prediction for this system, see Table 10.

The calculations predict an annual solar fraction of 50%. The average environmental temperature and solar radiation data used in the f-chart prediction compare tolerably well with the actual solar and environmental data during the monitoring period. The f-chart prediction shows that these collectors, operated in the non-tracking mode, should have converted 50% of the solar radiation striking them into useful heat. The performance data, however, showed that the actual tracking collectors only delivered 26% overall efficiency, or about half of the expected efficiency.

In the reference shown in the footnote below, there is a discussion of a system instrumented by the University of Texas which used 1280 ft^2 of Northrup collectors on an apartment building. Measured collector efficiencies were 60% of the manufacturer's performance curves. This was due, in part, to tracking errors. Tests of a single collector showed performance of 30% below the manufacturer's recommended performance curve.[1]

8.0 CONCLUSIONS

The monitoring results from this project showed a relatively low solar collector efficiency despite the utilization of a complex tracking and control system. Only a small fraction of the solar heat collected was eventually delivered to the house. This deficiency is primarily related to the low operating temperature of the solar system, which is not well matched to the high temperature requirements of the heat distribution system of the house.

Records of utility consumption and degree-day data are included for reference in Tables 11 and 12.

[1]Proceedings of the Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, March 26-28, 1980, "Active Heating/Cooling Systems Support" by Charles Bishop from SERI, page 8.

TABLE 1

KILBY HOUSE HEAT LOAD

	R	U (Btu/hr ft^2 ^oF)	Area (sq. ft.)	U X A
Ceiling & Roof	52.49	0.019	2072	39
East Walls	14.88	0.067	891	60
West Addition	13.03	0.077	623	48
Windows	1.72	0.580	205	119
Basement Walls	*60	0.017	1654	28
Basement Floor	*80	0.012	2072	26
Basement Windows	1.72	0.580	20	11
**Infiltration: 16576 ft^3 X $\frac{1}{2}$ X 0.18				149
				480 Btu/hr^{-1} $^oF^{-1}$ or 0.91 MJ/hr^{-1} $^oC^{-1}$

*Equivalent

**Assuming $\frac{1}{2}$ air change/hour

TABLE 2

LOG OF FLOW IN COLLECTOR LOOP

M / D	HOUR	METER READING	TOTAL FLOW	ON TIME	AVERAGE FLOW	
		(gal x 10^{-1})	(gal.)	(hr.)	(gph)	(lpm)
3/ 5	17	000754				
			3060	4.71	650	41
3/ 6	19	001060				
			2260	3.47	651	41
3/ 7	18	001286				
			1230	1.91	644	40.6
3/10	18	001409				
			14230	21.48	662	41.8
3/14	16	002832				
			1560	2.1	743	46.9
3/15	18	002988				
			6900	9.87	699	44.1
3/22	16	003678				
			2060	4.64	444	28
3/23	18	003884				
			*	*	*	*
4/ 3	20	004187				
			6640	10.03	662	41.8
4/ 3	18	004851				
			2910	4.28	680	42.9
4/ 6	19	005142				
			*	*	*	*
4/10	8	005694				
			1880	3.24	580	36.6
4/11	19	005882				
			5640	8.6	656	41.4
4/12	20	006446				
			4980	7.43	670	42.3
4/13	19	006944				
			2740	4.19	654	41.3
4/14	19	007218				
			13340	24.79	538	33.9
4/17	19	008552				
		TOTALS	69430	102.15	AVG. 679.7	42.9

*Missing Data and Leaking

TABLE 3

SAMPLE OF HOURLY DATA AND DAILY SUMMARY

DAILY PERFORMANCE SUMMARY FOR THE KILBY HOUSE 4/ 13/80

HR	SOLAR INSOL (KWM-2)	SOLAR INPUT (MJ)	COLL OUTPUT (MJ)	SOLAR DHWX (MJ)	SOLAR STORE (MJ)	SOLAR HOUSE (MJ)	AUX HOUSE (MJ)	SUM INPUT (MJ)	HOUSE LOAD (MJ)	MECH ROOM (C)	STORE TEMP (C)	AMBT TEMP (C)	HOUSE TEMP (C)	DELTA STORE (MJ)	STORE LOSS (MJ)	AUX POWER (MJ)
1	.0	.0	.0	.0	.0	.0	6.6	13.6	15.2	24.4	51.3	6.0	22.8	-1.5	-1.1	.0
2	.0	.0	.0	.0	.0	.0	6.8	11.8	15.4	23.9	51.2	5.7	22.6	-1.3	-1.1	.0
3	.0	.0	.0	.0	.0	.0	12.3	17.3	15.5	23.5	51.1	5.6	22.7	-1.5	-1.2	.0
4	.0	.0	.0	.0	.0	.0	9.2	14.2	15.5	23.1	51.0	5.5	22.5	-1.5	-1.2	.0
5	.0	.0	.0	.0	.0	.0	10.4	15.4	15.7	22.7	50.9	5.3	22.5	-1.5	-1.2	.0
6	.0	.0	.0	.0	.0	.0	10.4	15.4	15.8	22.4	50.8	5.1	22.5	-1.6	-1.2	.0
7	.0	2.1	.0	.0	.0	.0	13.1	18.1	14.5	22.2	50.7	6.7	22.5	-1.4	-1.2	.0
8	.2	24.6	.0	.0	.0	.0	6.4	11.4	12.2	22.1	50.6	9.3	22.7	-1.3	-1.2	.0
9	.4	80.1	.0	.0	-1.2	1.2	4.3	10.6	9.9	22.3	50.6	11.8	22.6	-1.3	-1.2	.3
10	.7	101.6	21.9	.0	18.3	3.6	.0	8.6	7.5	23.2	49.9	14.4	22.6	-10.2	-1.1	1.3
11	.9	111.9	46.9	.0	44.3	2.6	.0	7.6	5.0	25.1	49.9	17.3	22.8	-.8	-1.0	1.9
12	1.0	115.0	47.1	.0	44.9	2.2	.0	7.2	3.1	26.7	51.9	19.5	22.9	32.0	-1.0	1.9
13	1.0	107.8	41.6	.0	39.8	1.8	.0	6.8	1.6	28.1	53.9	21.2	22.9	31.9	-1.1	1.9
14	.9	102.6	35.1	.0	35.5	2.7	.0	7.7	.4	29.2	55.7	22.4	22.8	27.0	-1.1	1.9
15	.7	86.2	27.6	.0	26.7	.9	.0	5.9	.4	29.6	56.8	22.6	23.0	17.6	-1.1	1.9
16	.5	83.1	28.8	.0	27.0	1.8	.0	6.8	.2	30.0	57.9	22.7	22.9	16.5	-1.2	2.0
17	.3	73.9	20.6	.0	10.9	9.7	.0	14.7	.5	27.7	58.3	22.4	22.9	6.3	-1.3	1.2
18	.2	35.9	5.3	.0	1.5	3.9	.0	8.9	.5	27.7	58.2	22.7	23.3	-.3	-1.3	.8
19	.0	4.1	.0	.0	-21.6	21.6	.0	26.6	1.7	27.7	58.1	21.5	23.3	-1.9	-1.3	.4
20	.0	.0	.0	.0	-.2	.2	7.9	13.1	5.4	27.7	58.1	17.5	23.4	-.8	-1.3	.0
21	.0	.0	.0	.0	.0	.0	19.8	24.8	8.5	27.7	58.0	14.3	23.6	-.9	-1.3	.0
22	.0	.0	.0	.0	.0	.0	19.7	24.7	10.0	30.0	57.9	12.5	23.5	-1.3	-1.2	.0
23	.0	.0	.0	.0	.0	.0	20.1	25.1	11.3	29.6	57.8	10.7	23.1	-1.4	-1.2	.0
0	.0	.0	.0	.0	.0	.0	22.5	27.5	12.2	29.2	57.8	9.6	23.0	-1.1	-1.2	.0
	7.2	931.0	278.1	.0	225.9	52.2	171.4	343.6	197.8	26.1	54.1	13.8	22.9	101.7	-28.0	15.6

TABLE 4

DAILY SUMMARY DATA FOR MARCH

DAILY PERFORMANCE SUMMARY FOR THE KILBY HOUSE

	DA	SOLAR INSOL (KWM-2)	SOLAR INPUT (MJ)	COLL OUTPUT (MJ)	SOLAR DHWX (MJ)	SOLAR STORE (MJ)	SOLAR HOUSE (MJ)	AUX HOUSE (MJ)	SUM INPUT (MJ)	HOUSE LOAD (MJ)	MECH ROOM (C)	STORE TEMP (C)	AMBT TEMP (C)	HOUSE TEMP (C)	DELTA STORE (MJ)	STORE LOSS (MJ)	AUX POWER (MJ)
	1	2.2	322.3	108.4	22.0	86.3	.1	111.3	161.4	176.3	20.1	33.8	1.1	22.7	67.3	-5.7	9.3
	2	4.4	470.1	104.2	43.3	43.4	17.5	262.5	400.0	456.4	17.8	34.2	1.7	22.6	10.6	-16.4	10.8
	3	2.3	115.0	.0	.0	.0	.0	703.1	823.1	782.0	18.1	34.4	-13.3	22.5	-18.7	-16.2	.0
	4	1.2	138.6	.0	.0	.0	.0	923.0	1043.0	896.4	17.8	33.1	-18.4	22.7	-19.7	-15.4	.0
	5	3.5	367.5	.0	1.1	-1.1	.0	950.0	1070.0	845.4	18.2	31.9	-16.1	22.6	-19.2	-13.7	.3
	6	6.4	742.1	196.0	58.4	130.0	7.5	792.9	920.4	640.0	17.4	33.4	-6.5	22.8	89.1	-16.0	15.2
	7	4.9	491.7	72.6	23.9	48.6	.0	613.9	733.9	690.7	17.7	36.0	-4.6	22.9	-8.0	-18.3	16.8
	8	3.5	87.3	4.3	-9.6	13.8	.0	506.7	626.7	593.3	15.8	33.4	-1.0	22.0	-36.2	-17.5	5.5
	9	2.1	66.7	.0	.0	-.3	.2	391.5	511.7	438.4	16.1	33.1	3.0	23.1	-15.1	-17.0	.6
	10	3.3	312.0	33.2	49.8	-16.8	.2	371.8	492.0	462.9	17.2	30.9	1.7	22.9	-48.3	-13.7	9.4
	11	4.6	487.6	87.7	119.4	-34.9	5.1	297.1	422.3	362.9	18.2	27.7	6.3	22.9	-15.6	-11.5	18.2
*	12	5.6	655.9	176.4		39.3	.0	405.8	525.8	472.0	17.7	27.7	1.2	22.8	44.3	-12.0	25.7
	13	6.8	833.5	258.7		67.5	78.7	359.1	557.8	431.8	18.8	33.5	2.8	22.5	91.9	-14.7	26.2
	14	5.0	525.5	131.4	.1	24.1	107.2	232.7	454.8	378.3	19.4	38.0	4.4	22.5	33.4	-17.9	19.4
	15	4.5	449.6	84.0	.3	22.8	60.9	279.9	460.8	501.3	18.2	39.3	-.1	22.9	.3	-21.1	7.4
	16	6.8	865.3	218.6	.0	97.4	121.1	274.0	535.1	498.3	19.0	40.8	-.3	22.5	30.9	-21.8	19.9
	17	2.3	55.4	.0	.0	.0	.0	506.7	626.7	395.6	16.8	40.5	3.6	21.8	-22.9	-23.7	.0
	18	6.1	164.2	.0	.0	.0	.0	290.7	410.7	343.6	17.1	39.1	5.6	21.3	-21.7	-22.0	.0
	19	2.5	64.7	.0	.0	.0	.0	280.7	400.7	431.9	16.6	37.7	1.5	21.3	-24.1	-21.1	.0
	20	7.2	212.5	.0	.0	.0	.0	321.4	441.4	397.7	17.0	36.2	3.7	21.9	-21.4	-19.3	.0
	21	2.8	97.5	.0	.0	.0	.0	249.5	369.5	474.9	16.5	34.8	.2	22.0	-23.1	-18.3	.0
	22	7.3	221.7	1.5	.0	1.4	.1	221.5	341.5	402.8	16.9	32.5	3.6	22.0	-67.8	-15.6	1.1
	23	5.9	627.1	158.6	.0	151.8	6.8	158.0	284.7	396.1	17.8	33.1	4.1	22.2	102.7	-15.2	10.1
	24	2.9	86.2	.0	.0	.0	.0	317.2	437.2	496.3	16.9	35.7	-.7	22.0	-18.4	-18.9	.0
	25	2.8	253.5	.0	.0	.0	.0	371.7	491.7	533.6	17.0	34.6	-2.5	22.0	-18.5	-17.6	6.9
**											17.8	34.3	1.1	21.8	37.4	-12.4	15.3
	27	.1	.0	.0	.0	.0	.0	33.3	58.3	88.0	17.2	34.0	2.8	22.1	-38.5	-3.5	.9
	28	7.7	787.3	1.5	.0	-1.5	3.0	205.0	327.9	390.4	17.0	33.4	4.2	22.1	-16.7	-18.4	.2
	29	5.4	538.9	.0	.0	.0	.0	245.2	355.2	350.3	16.7	32.3	6.3	22.3	-16.9	-15.7	.0
	30	1.6	108.8	.0	.0	.0	.0	314.9	434.9	499.6	16.8	31.2	-.6	22.3	-17.6	-14.5	.0
	31	2.3	126.3	.0	.0	.0	.0	411.0	526.0	595.3	16.8	30.2	-1.7	22.4	-16.9	-12.8	.0

* Domestic hot water preheat tank begins to leak and is removed from the system
**Shorted probe, invalid data

TABLE 5

DAILY SUMMARY DATA FOR APRIL

DAILY PERFORMANCE SUMMARY FOR THE KILBY HOUSE

	DA	SOLAR INSOL (KWM-2)	SOLAR INPUT (MJ)	COLL OUTPUT (MJ)	SOLAR DHWX (MJ)	SOLAR STORE (MJ)	SOLAR HOUSE (MJ)	AUX HOUSE (MJ)	SUN INPUT (MJ)	HOUSE LOAD (MJ)	MECH ROOM (C)	STORE TEMP (C)	AMBT TEMP (C)	HOUSE TEMP (C)	DELTA STORE (MJ)	STORE LOSS (MJ)	AUX POWER (MJ)
	1	2.6	309.0	.0	.0	.0	.0	323.2	448.2	514.9	16.7	29.2	-.2	22.4	-16.4	-13.0	.0
	2	3.2	334.6	.0	.0	.0	.0	326.4	446.4	481.7	17.9	28.2	.4	22.5	-14.2	-10.4	.0
	3	7.4	866.3	210.9	.0	175.7	35.2	254.7	409.9	436.1	18.3	30.4	2.4	22.4	115.0	-12.1	12.6
	4	7.8	841.7	153.7	.0	88.7	65.0	185.1	370.1	359.9	19.4	37.8	5.9	22.3	117.7	-18.4	11.1
	5	5.9	696.9	128.0	.0	88.8	39.2	137.9	297.1	317.6	22.2	43.3	8.1	22.7	56.5	-21.1	12.4
	6	6.5	712.3	98.0	.0	45.0	53.0	80.8	253.8	353.4	23.1	46.3	6.6	22.7	16.2	-23.2	13.4
	7	4.1	453.7	51.1	.0	-143.5	194.6	155.6	465.2	370.1	20.9	39.9	4.1	21.8		-18.2	12.7
*																	
	10	2.9	93.4	.0	.0	.0	.0	255.2	375.2	414.4	17.0	32.5	3.6	22.5	-4.6	-15.5	.0
	11	4.7	495.8	145.7	.0	115.1	30.6	209.2	359.8	399.9	17.9	33.5	4.1	22.4	49.5	-15.6	9.6
	12	7.8	1052.1	397.5	.0	344.5	53.0	127.3	300.2	355.8	21.9	42.8	6.1	22.4	253.6	-20.9	18.6
	13	7.2	931.0	278.1	.0	225.9	52.2	171.4	343.6	197.8	26.1	54.1	13.8	22.9	101.7	-28.0	15.6
	14	6.2	756.5	179.3	.0	158.9	20.4	51.7	192.1	196.3	27.6	58.0	14.1	23.0	30.9	-30.4	11.2
	15	5.8	835.5	283.6	.0	249.3	34.3	27.4	181.7	267.2	28.0	56.7	10.6	22.8	-65.2	-28.7	17.9
	16	7.6	1045.9	356.1	.0	237.9	118.2	.0	238.2	237.6	27.0	54.9	11.4	22.3	63.1	-27.9	22.9
	17	7.7	1049.0	368.9	.0	274.3	74.6	.0	174.6	132.1	26.9	60.5	16.6	22.7	90.3	-33.6	20.7
	18	7.3	948.4	314.5	.0	308.1	6.4	22.9	149.3	148.2	26.6	68.6	16.3	23.0	133.5	-41.9	18.6
	19	6.0	783.2	147.6	.1	143.8	3.7	38.1	161.9	130.4	27.2	72.4	17.3	23.2	-21.9	-45.2	12.6
	20	7.8	790.4	150.2	.4	149.8	.0	2.9	122.9	71.5	27.4	71.5	20.8	24.0	-23.3	-44.1	4.8
	21	7.0	920.7	402.5	.0	402.5	.0	.0	120.0	220.5	27.7	72.4	13.5	23.6	59.0	-44.7	14.8
**	22	2.8	306.9	19.0	.0	-85.9	104.8	.0	224.8	318.5	27.7	64.8	8.3	22.8	-316.4	-37.1	10.4
	23	6.7	889.9	300	.0	420.3	99.6	.0	219.6	180.2	27.7	52.2	14.4	22.7	-30.1	-24.5	25.1
	24	6.6	800.6	250	.0	483.2	46.6	.0	166.6	138.7	27.7	47.8	16.8	23.1	-130.3	-20.1	25.5
	25	7.6	1050.0	450	.0	413.9	39.1	.0	159.1	164.0	27.8	52.0	15.6	23.1	259.5	-24.3	24.1
	26	7.6	1066.5	500	.0	468.5	26.6	.0	146.6	172.5	27.7	64.7	15.4	23.3	160.4	-37.0	29.8
	27	7.9	573.8	-.0	.0	-21.1	21.1	1.6	142.7	163.6	27.7	63.9	16.6	24.1	-63.8	-41.2	3.0
	28	7.3	542.0	.5	.0	.5	.0	.0	120.0	104.7	28.5	64.9	18.9	23.7	-59.4	-36.4	.2
	29	6.2	280.2	.0	.0	.0	.0	.0	120.0	113.3	27.4	61.4	18.4	23.6	-54.8	-35.9	1.9
	30	1.8	70.8	.0	.0	.0	.0	.0	110.0	222.9	24.5	58.1	11.5	22.6	-46.9	-30.8	7.3

* Lost data, tape not changed
**Solar pump replaced

TABLE 6

DAILY SUMMARY DATA FOR MAY

DAILY PERFORMANCE SUMMARY FOR THE KILBY HOUSE

DA	SOLAR INSOL (KWM-2)	SOLAR INPUT (MJ)	COLL OUTPUT (MJ)	SOLAR DHWX (MJ)	SOLAR STORE (MJ)	SOLAR HOUSE (MJ)	AUX HOUSE (MJ)	SUM INPUT (MJ)	HOUSE LOAD (MJ)	MECH ROOM (C)	STORE TEMP (C)	AMBT TEMP (C)	HOUSE TEMP (C)	DELTA STORE (MJ)	STORE LOSS (MJ)	AUX POWER (MJ)
3	1.9	104.7	-1.9	.1	-45.5	43.5	20.8	144.3	215.5	24.1	33.1	8.3	23.1		-6.0	2.0
4	7.4	1055.2	478.3	.0	453.8	24.5	61.4	205.9	205.5	24.3	42.8	13.9	23.3	319.9	-18.6	17.8
5	7.6	1043.9	480.4	.0	372.8	107.5	.0	227.5	140.9	27.7	58.2	16.8	23.3	191.8	-30.5	19.6
6	6.8	924.8	373.9	.0	353.8	20.1	.0	140.1	159.3	27.7	65.6	16.0	23.3	42.0	-37.9	17.7
7	5.2	692.5	144.1	.0	83.8	60.3	.0	180.3	205.8	27.7	62.4	13.4	22.9	-154.6	-34.7	13.6
8	5.6	620.0	171.0	.0	33.5	137.5	.0	257.5	195.9	27.7	51.7	13.6	22.6	-95.6	-24.0	15.4
9	1.6	108.8	.0	.0	-67.1	67.1	.0	187.1	260.1	27.7	46.5	10.8	22.7	-160.4	-18.8	9.1
10	3.9	376.5	31.2	.0	-56.6	87.8	38.3	246.0	278.3	27.1	36.4	9.7	22.4	-78.7	-9.4	7.4
11	7.5	1050.0	478.4	.0	453.8	24.6	133.7	278.3	276.1	25.9	43.7	9.0	22.6	269.2	-17.8	18.3
12	6.8	878.1	350.8	.0	276.6	74.3	.0	194.3	218.9	27.7	56.4	10.6	20.6	84.5	-28.7	17.9
13	7.1	937.1	340.5	.0	158.0	182.5	.0	302.5	223.0	27.7	53.0	12.2	22.4	-42.8	-25.3	18.6
14	6.9	981.3	405.8	.0	277.3	129.6	.0	249.6	208.8	27.7	54.8	13.0	22.5	51.6	-27.1	19.6
15	7.2	975.1	257.0	.0	166.7	90.3	.0	210.3	176.4	27.7	57.6	14.6	22.7	32.5	-29.9	19.8
16	6.5	844.8	225.8	.0	171.8	34.0	.0	154.0	148.3	27.7	60.1	16.2	23.0	9.2	-32.4	17.7
17	6.0	848.9	228.5	.0	213.3	15.2	.0	135.2	159.7	27.7	61.4	16.0	23.3	32.5	-33.7	17.9
18	6.4	857.1	187.1	.0	-71.3	258.4	.0	378.4	125.9	27.7	65.7	18.1	23.9	83.1	-35.0	17.4

TABLE 7

SYSTEM FAILURES DURING MONITORING PERIOD

MARCH | APRIL | MAY 19

11 DHW Preheat Tank developed leak - removed from system 19

23 Furnace probe shorted underground 20

23 Solar Collector Pump replaced 19

26 System off 3

Collector leaks

TABLE 8

OVERALL PERFORMANCE SUMMARY OF KILBY SOLAR SYSTEM

MONTH	DAYS	SOLAR INPUT MJ	COLLECTOR OUTPUT MJ	PUMP POWER MJ	SOLAR TO HOUSE MJ	ELECTRIC MJ	AUX HOUSE MJ	SUM INPUT MJ	HOUSE LOAD MJ	HOUSE TEMP °C	AMBIENT TEMP °C
March	30	10,266	1,634	209	407	3,323	11,424	15,254	14,873	22.4	-0.3
April	27	19,497	5,185	348	1,119	3,405	2,316	6,840	6,781	22.6	11.1
May	16	12,224	4,151	259	1,308	1,929	254	3,491	3,214	22.9	13.7
TOTALS	73	41,987	10,970	816	2,834	8,657	13,994	25,585			
DISTRIBUTION					11%	34%	55%	100%			

Overall Collector Efficiency $= \frac{10,970}{41,987} \times 100 = 26\%$ Collector COP $= \frac{10,970}{816} = 13.4$ Overall COP $= \frac{2834}{816} = 3.4$

TABLE 9

INSOLATION COMPARISON AT KILBY SITE, $kWh\text{-}m^{-2}\text{-}day^{-1}$

MONTH	MEASURED GREAT FALLS @ 60°	CALCULATED GREAT FALLS @ 45°	MEASURED KILBY SITE
March	4.2	4.28	4.19
April	5.2	5.56	5.66

TABLE 10

PERFORMANCE PREDICTION USING F-CHART

	----DAILY----		---MONTHLY---						
MON	SOLAR RAD KWh/m2	AMBT TEMP (C)	DEGREE DAYS (C-DAY)	WATER LOAD KWh	HEAT LOAD KWh	TOTAL LOAD KWh	SOLAR FRAC (%)	SOLAR ENERGY KWh	BACKUP ENERGY KWh
JAN	2.5	-6.4	767	0	4655	4655	23	1093	3562
FEB	3.4	-3.0	597	0	3626	3626	41	1500	2126
MAR	4.3	-.8	594	0	3609	3609	52	1888	1721
APR	4.9	6.3	360	0	2186	2186	86	1873	313
MAY	4.8	11.8	204	0	1238	1238	100	1238	0
JUN	5.5	16.0	90	0	546	546	100	546	0
JUL	5.7	20.7	10	0	61	61	100	60	1
AUG	5.4	19.7	23	0	142	142	100	141	1
SEP	4.9	14.1	144	0	877	877	100	877	0
OCT	4.1	9.1	291	0	1768	1768	85	1504	264
NOV	3.0	1.4	507	0	3076	3076	42	1288	1788
DEC	2.4	-3.1	663	0	4028	4028	25	1021	3007
YEAR	4.2	7.2	4250	0	25812	25812	50	13029	12783

YEARLY SOLAR FRACTION.... .50

CLIENT.................... KILBY
LOCATION.................. GREAT FALLS

COLLECTOR AREA........... 29.70 m2, 319.6 ft2
COLLECTOR TILT........... 45 DEGREES
COLLECTOR TYPE........... LIQUID
EFFICIENCY SLOPE......... 2.81 W/C-m2, .49 BTU/F-ft2
Y-INTERCEPT.............. .75
HOUSE LOAD FACTOR........ .25 KWh/C-HOUR, 479 BTU/F-HOUR

TABLE 11

MONTHLY UTILITY RECORDS OF GAS AND ELECTRIC

	1978		1979		1980	
	Gas ccf	Elec kWh	Gas ccf	Elec kWh	Gas ccf	Elec kWh
January	506	1200	370	1211	270	1116
February	512	1304	532	1148	390	1266
March	430	1355	404	1045	370	1128
April	384	1205	296	1086	340	1260
May	194	1080	256	1214	210	1125
June	142	968	140	995	50	1124
July	78	1133	56	796	80	966
August	28	1005	32	1048	40	960
September	20	954	24	914		
October	44	1061	34	948		
November	66	1141	58	1170		
December	194	1170	196	977		

TABLE 12

GREAT FALLS DEGREE DAY DATA
(Degrees Celsius)

Month	Long-Term Average	1978 Degree Days	1978 Ratio	1979 Degree Days	1979 Ratio
January	766	986	1.28	1004	1.31
February	597	783	1.31	717	1.21
March	594	536	.90	517	.87
April	360	345	.96	401	1.11
May	203	233	1.15	231	1.14
June	90	58	.64	61	.68
July	10	30	3.00	10	1.00
August	23	31	1.35	8	.35
September	144	131	.91	58	.40
October	291	275	.94	267	.92
November	506	682	1.35	521	1.02
December	663	818	1.23	518	.78
TOTAL	4257	4908	1.15	4313	1.01

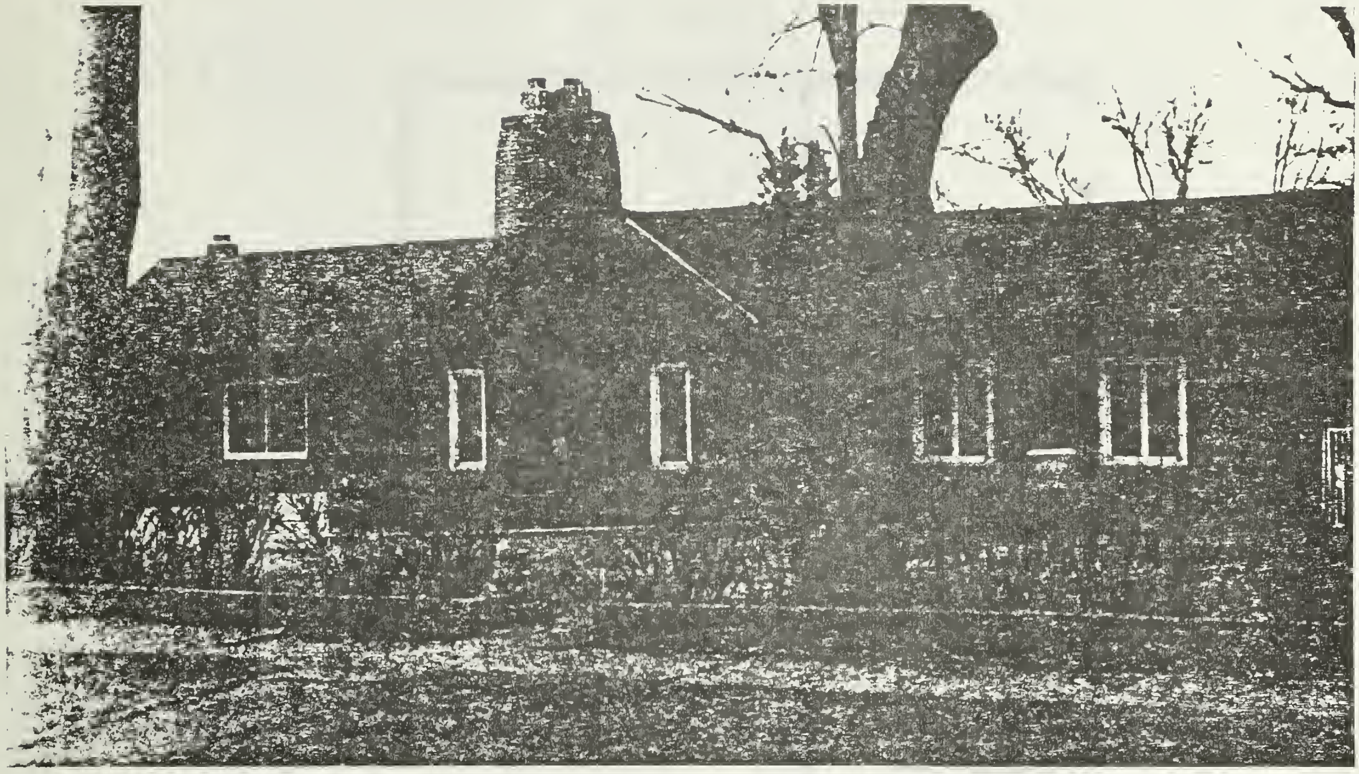


Figure 1: Front View of Kilby House

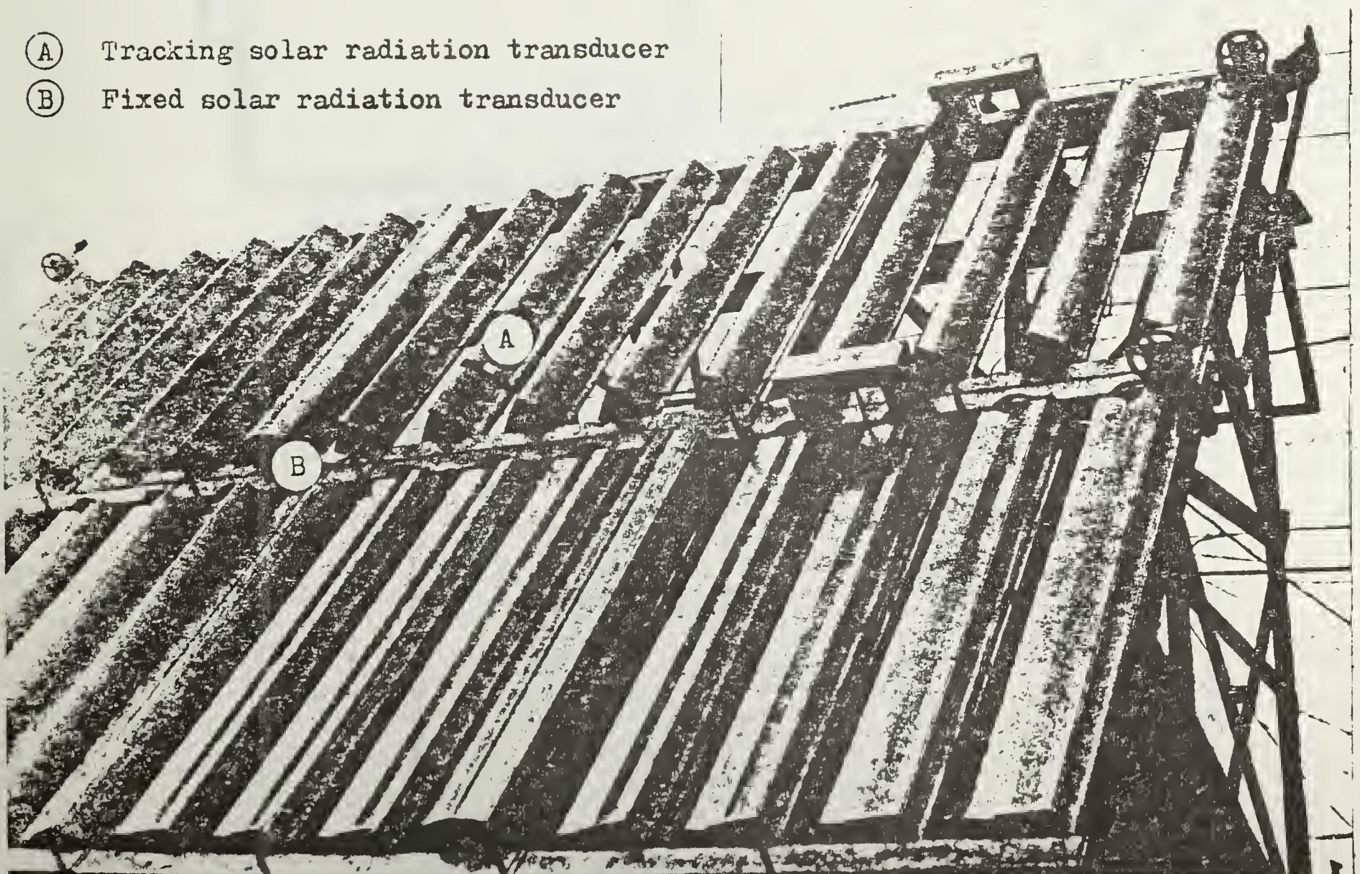
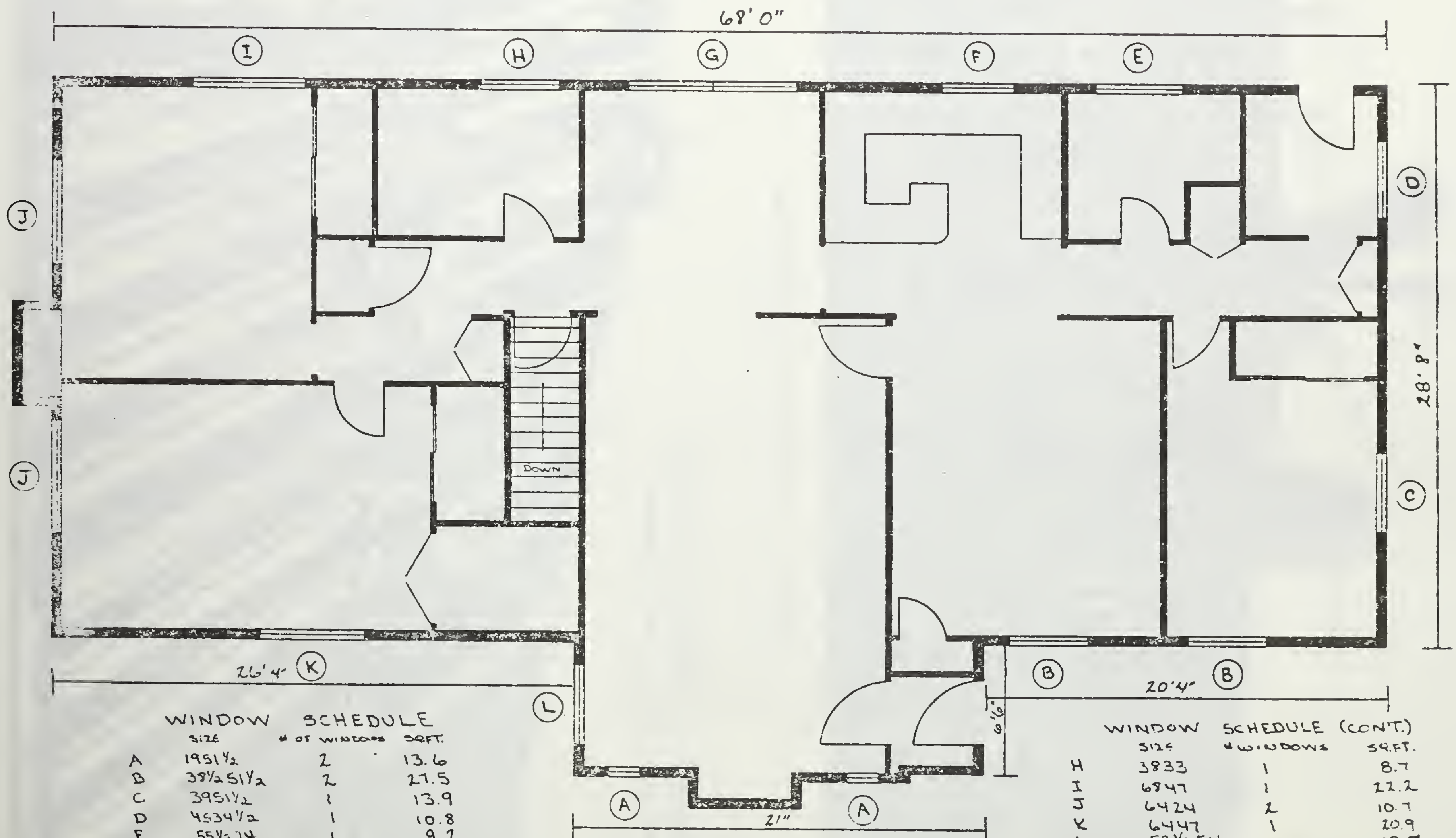


Figure 2: Collector Array



WINDOW SCHEDULE

	SIZE	# OF WINDOWS	SQ.FT.
A	1951½	2	13.6
B	38½51½	2	27.5
C	3951½	1	13.9
D	4534½	1	10.8
E	55½24	1	9.2
F	4449	1	14.9
G	10181	1	56.8

WINDOW SCHEDULE (CON'T.)

	SIZE	# WINDOWS	SQ.FT.
H	3833	1	8.7
I	6847	1	22.2
J	6424	2	10.7
K	6447	1	20.9
L	52½54	1	19.7
TOTALS		15	228.9

Figure 3: Floor Plan of Kilby House

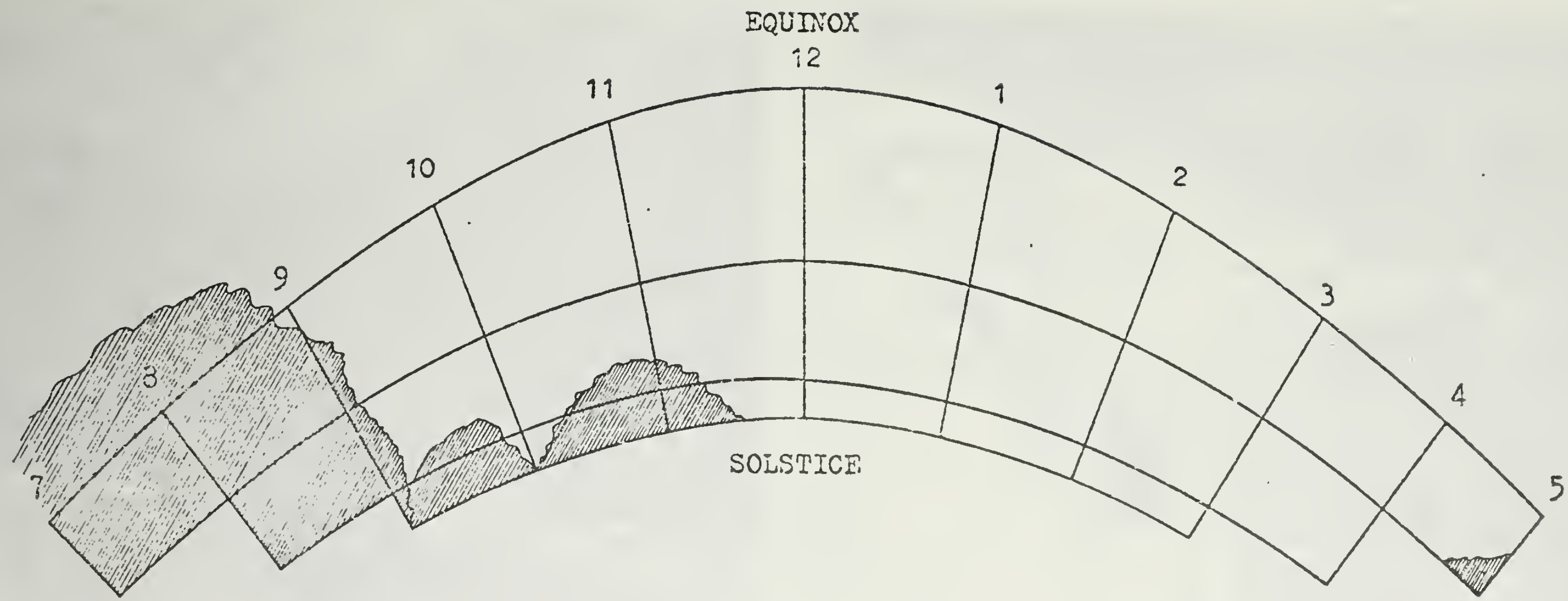
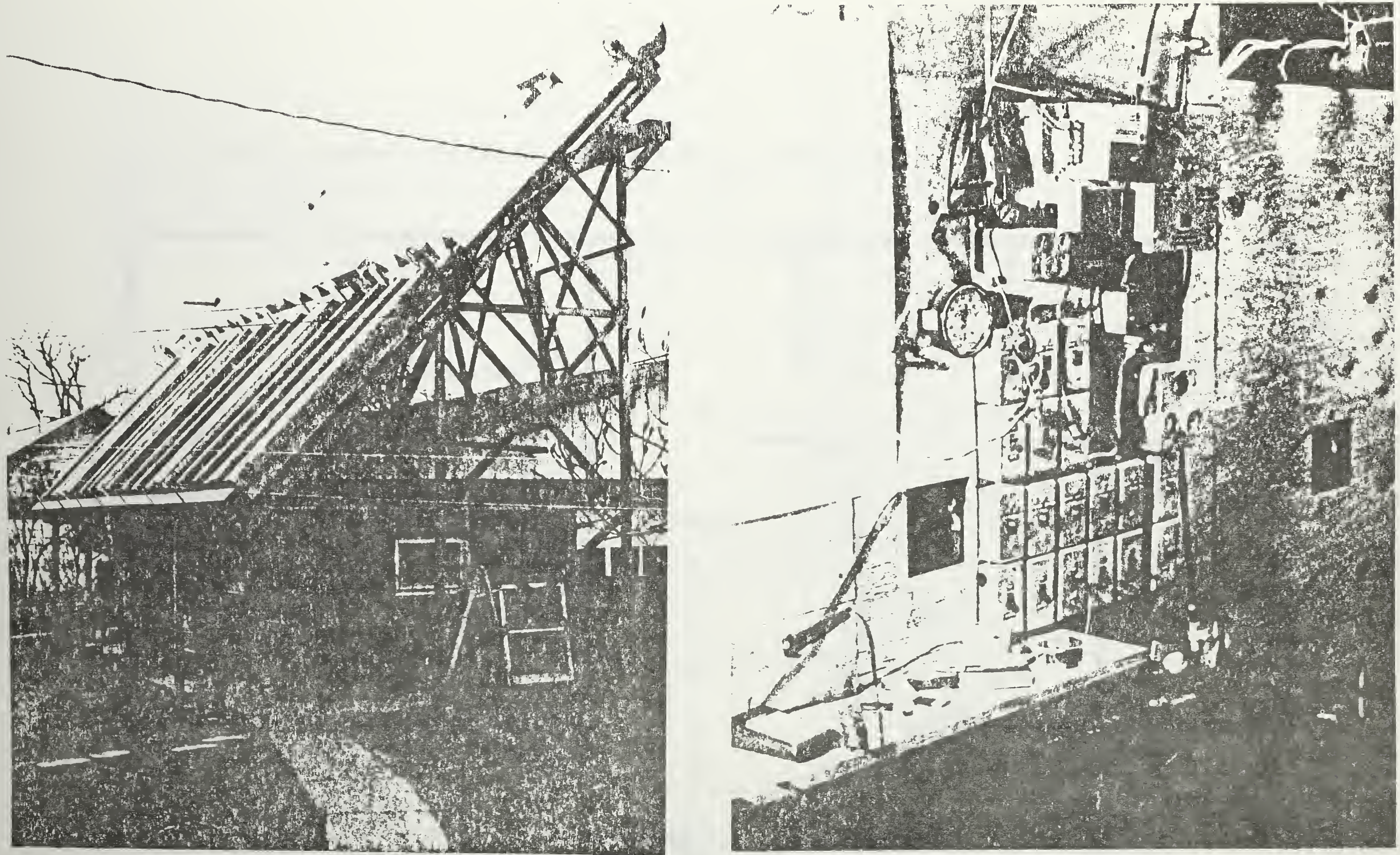


Figure 4: Shading Diagram for Concentrating Collector Array



(a) Tracking concentrating collectors

(b) System control panel

Figure 5: Kilby Solar System

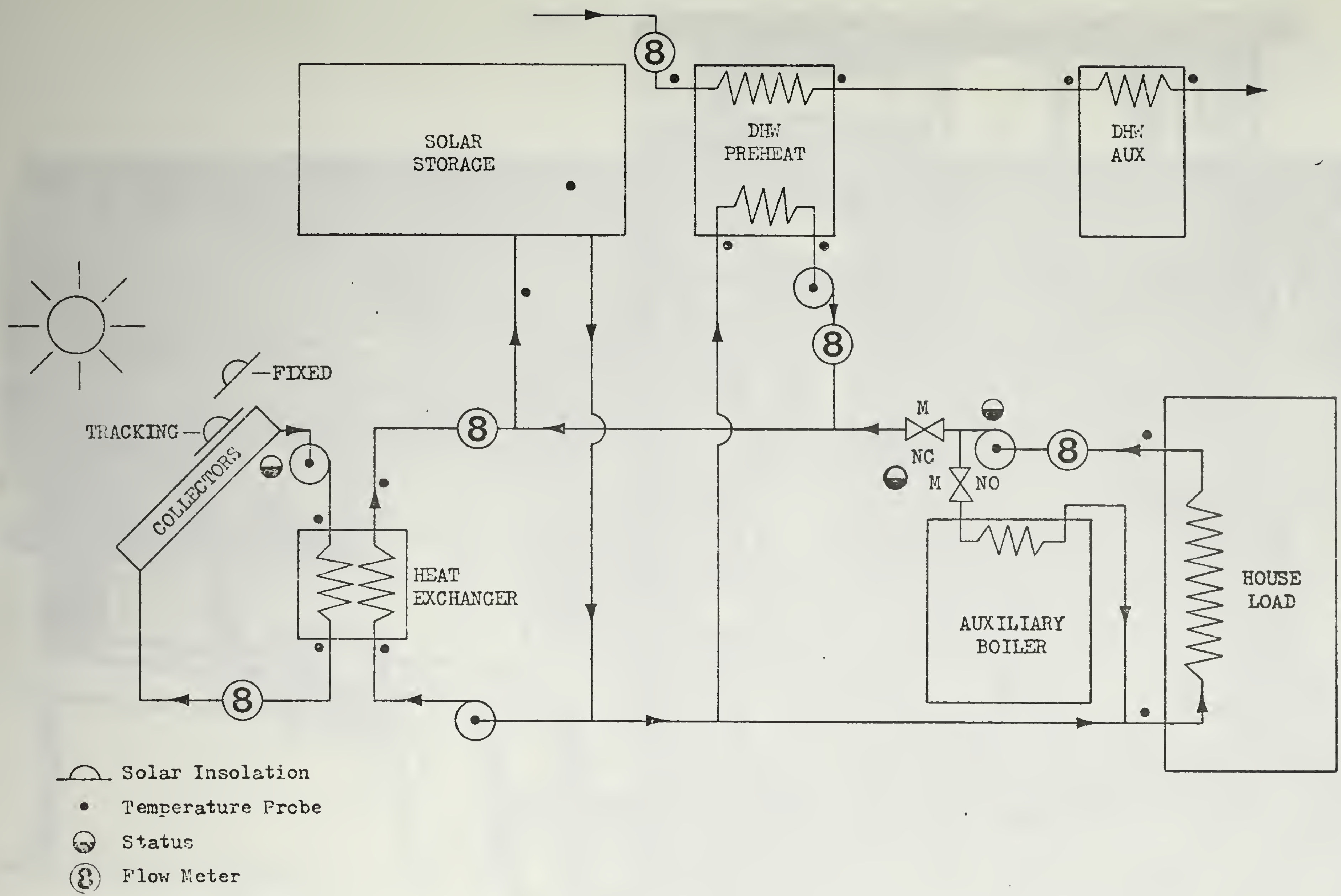


Figure 6: Schematic of Kilby Solar System Showing Placement of Monitoring Transducers

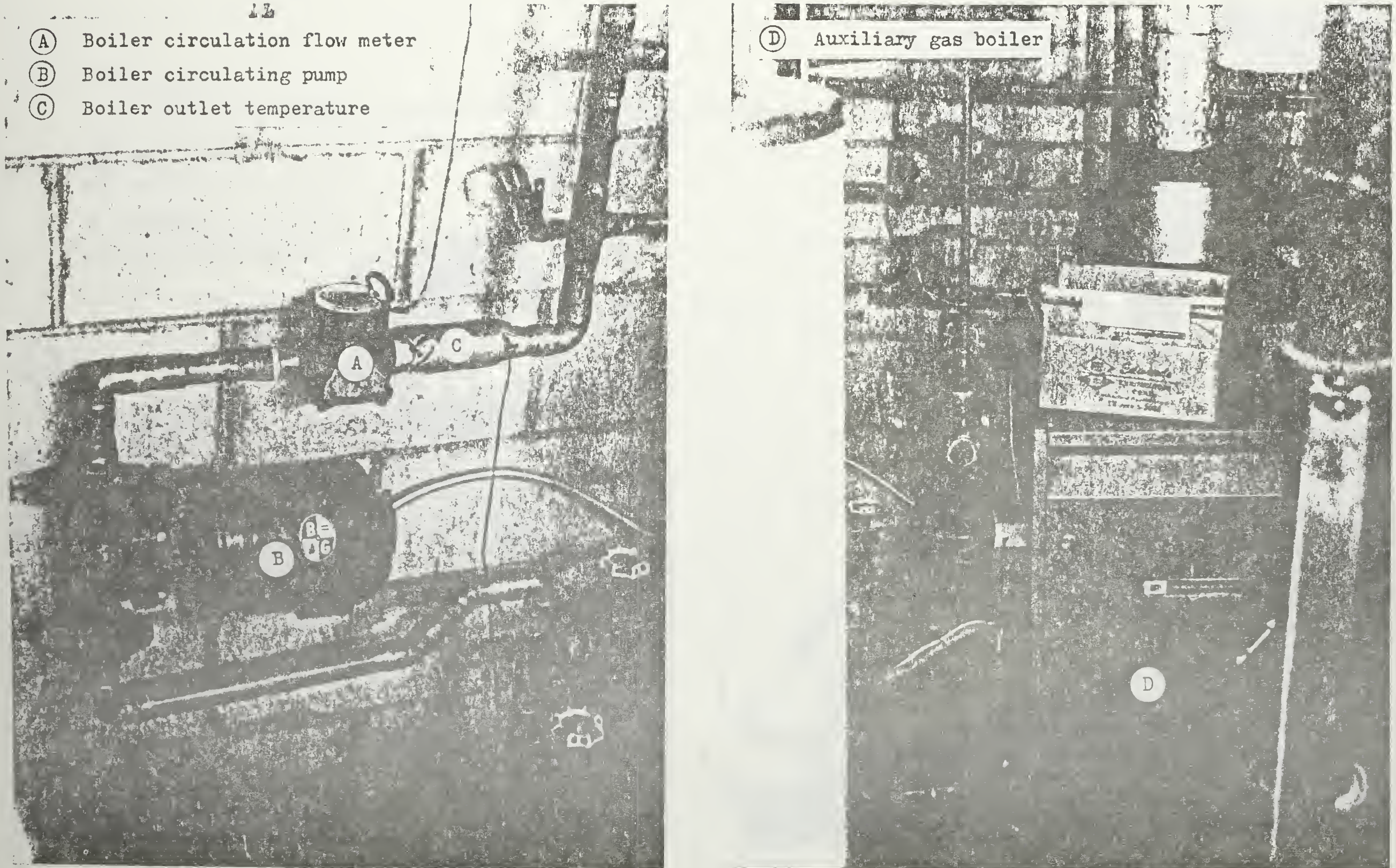
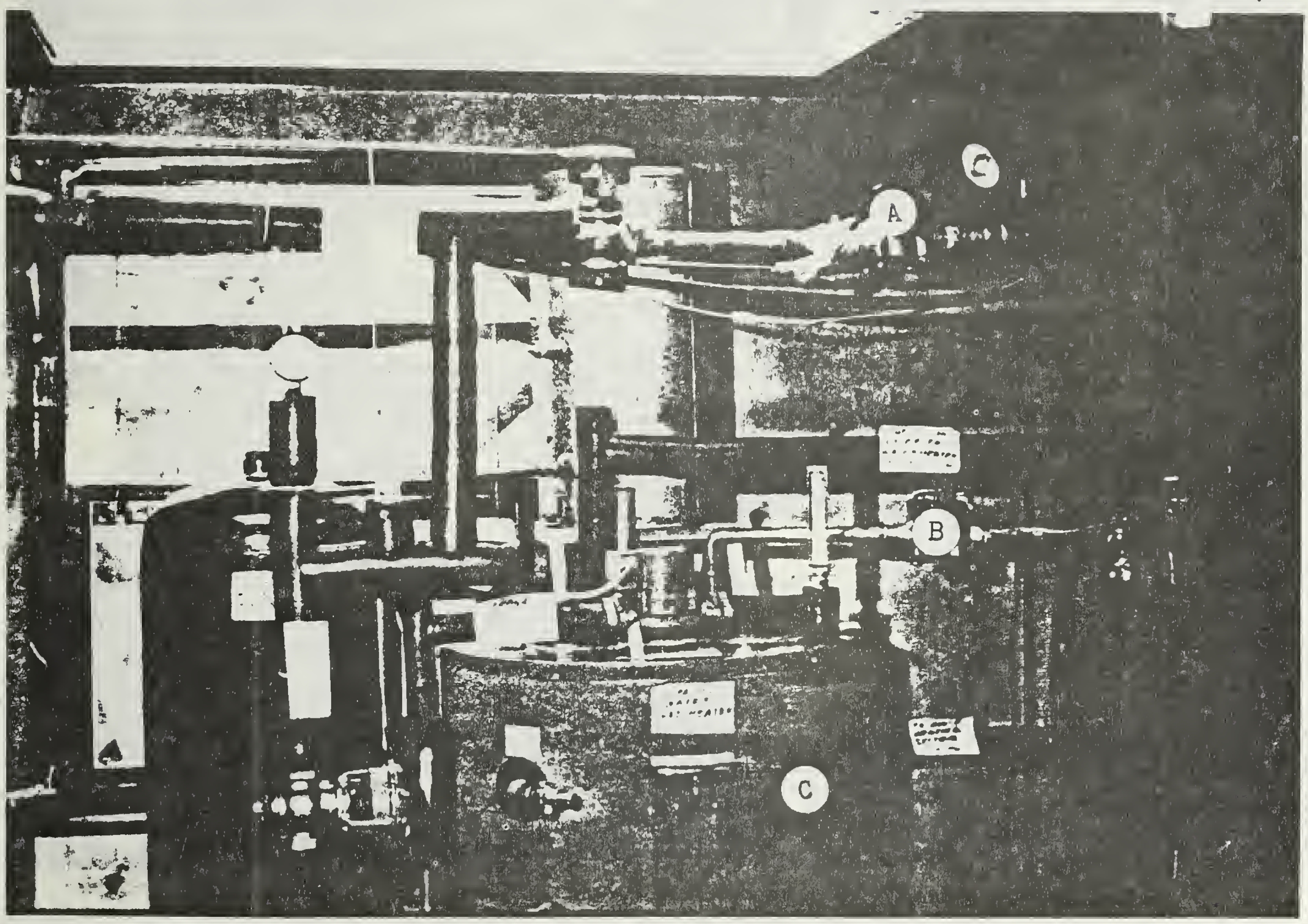


Figure 7: Auxiliary Gas Boiler

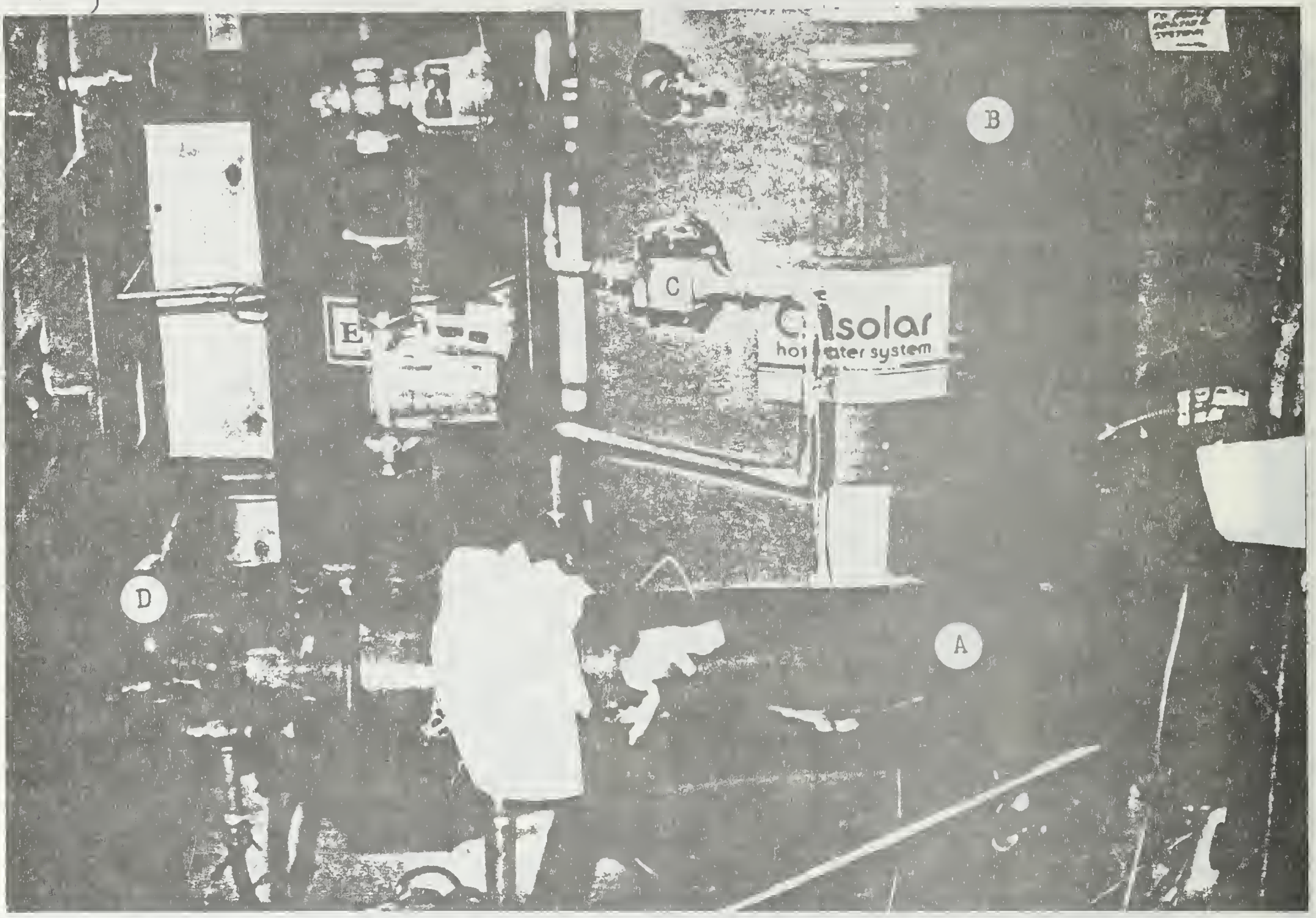


(A) Collector loop flow meter

(B) DHW flow meter

(C) Solar DHW preheat tank

Figure 8: Solar Heat Exchangers, Pumps and Plumbing



(A) Solar collector heat exchanger

(B) Solar DHW preheat tank

(C) Solar to DHW flow meter

(D) Storage loop flow meter

Figure 9: Solar Heat Exchangers

TYPES:

S - SOLAR
T - TEMP
DT - DUCT TEMP
ST - STATUS
P - POWER

FIGURE 10
TRANSDUCER LOG

KILBY HOUSE

DISK #	RS #	PROBE #	TYPE	LOCATION AND MOUNTING
1	1	3	S	Solar Transducer: Mounted on face of Tracking Collector
2	2		P	Auxiliary Electricity: Amp clamp in Solar System Control Room monitoring auxiliary power
3	5	4	S	Solar Transducer: Stationary mount facing south
4	6	relay	ST	Collector Pump Status: A relay connected in parallel with Collector Pump
5	7	relay	ST	House Circulation Pump Status: A relay in parallel with House Pump
6	8		ST	House Mode: Pneumatic switch to indicated Solar/Boiler mode
7	9		C	Collector Efficiency: Calculated on line
8	10		C	Collector Output: Calculated on line
9	11		C	Solar Heat to House: Calculated on line
10	12		C	Boiler Heat to House: Calculated on line
11	13	K-13	Flow	Domestic Hot Water Flow: A flow meter in the cold water line to the Domestic Hot Water Preheater
12	14	K-14	Flow	Solar to DHW Exchanger Flow: A flow meter in the line between the DHW Exchanger and the Storage Tanks
13	15	K-15	Flow	Solar Heat Exchanger Flow: A flow meter in the storage loop measuring flow through the Heat Exchanger
14	16	K-16	Flow	House Loop Flow: A flow meter in the house radiator loop measuring flow through the Radiators
15	17		T	Collector Inlet: A temperature probe on the pipe leading from the Heat Exchanger to the Collectors
16	18	34	T	Collector Outlet: A temperature probe on the pipe leading from the Collectors to the Heat Exchanger
17	19	19	T	Heat Exchanger Inlet: A temperature probe on the pipe leading from the Storage Tanks to the Heat Exchanger
18	20		T	Heat Exchanger Outlet: A temperature probe on the pipe leading from the Heat Exchanger to the Storage Tanks
19	21	25	T	Solar to the Preheat Tank: A temperature probe on the pipe leading from the Storage Tanks to the DHW Preheat Tank
20	22	6	T	Solar from DHW Preheat Tank: A temperature probe on the pipe leading from the DHW Preheat Tank to the Storage Tanks

TYPES:

S - SOLAR
T - TEMP
DT - DUCT TEMP
ST - STATUS
P - POWER

FIGURE 11
TRANSDUCER LOG

KILBY HOUSE (cont.)

DISK #	RS #	PROBE #	TYPE	LOCATION AND MOUNTING
21	23	2	T	From Solar Storage: A temperature probe on the pipe leading out of the Storage Tanks
22	24	35	T	Control Room Air Temperature: A temperature probe hanging from the ceiling of the Solar System Control Room
23	25	10	T	(DHW) Cold Water Inlet: A temperature probe on the inlet to the DHW Preheater from mains
24	26	1	T	(DHW) Preheated Water Outlet: A temperature probe on the outlet of the DHW Preheat Tank in Control Room
25	27	12	T	(DHW) Preheated Water Outlet/Auxiliary Heater Inlet: A temperature probe on the line from the Preheater to the Auxiliary Heater at the house
26	28	13	T	(DHW) Auxiliary Water Heater Outlet: A temperature probe on the hot water outlet pipe of the Auxiliary Water Heater
27	29	14	T	Hot Water to House Load: A temperature probe on the hot water pipe to the House Radiator System
28	30	15	T	Return from House Load: A temperature probe on the return pipe from the House Radiator System
29	31	17	T	House Air Temperature: A temperature probe in the Living Room
30	32	18	T	Ambient Air Temperature: A temperature probe behind the framework of the Collectors on the Garage Roof
31	33		C	Solar DHW at Preheat Tank: Calculated; heat added to DHW at the Preheat Tank
32	34		C	Solar DHW Line Loss: Calculated; heat lost in DHW between the Control Room and the House
33	35		C	Solar DHW Delivered to House: Calculated; heat added to DHW minus line loss
34	36		C	Auxiliary DHW: Heat added to the DHW by the Auxiliary Water Heater
35	37		C	Solar Heat from Exchanger: Calculated; Heat added to Storage System Loop
36	38		C	Solar to DHW Tank: Calculated; heat to DHW Heat Exchanger
37	39		C	Solar to Storage: Calculated; heat to Storage Tanks
38	40		T	Storage Temperature: A set of averaging temperature probes on the Storage Tanks

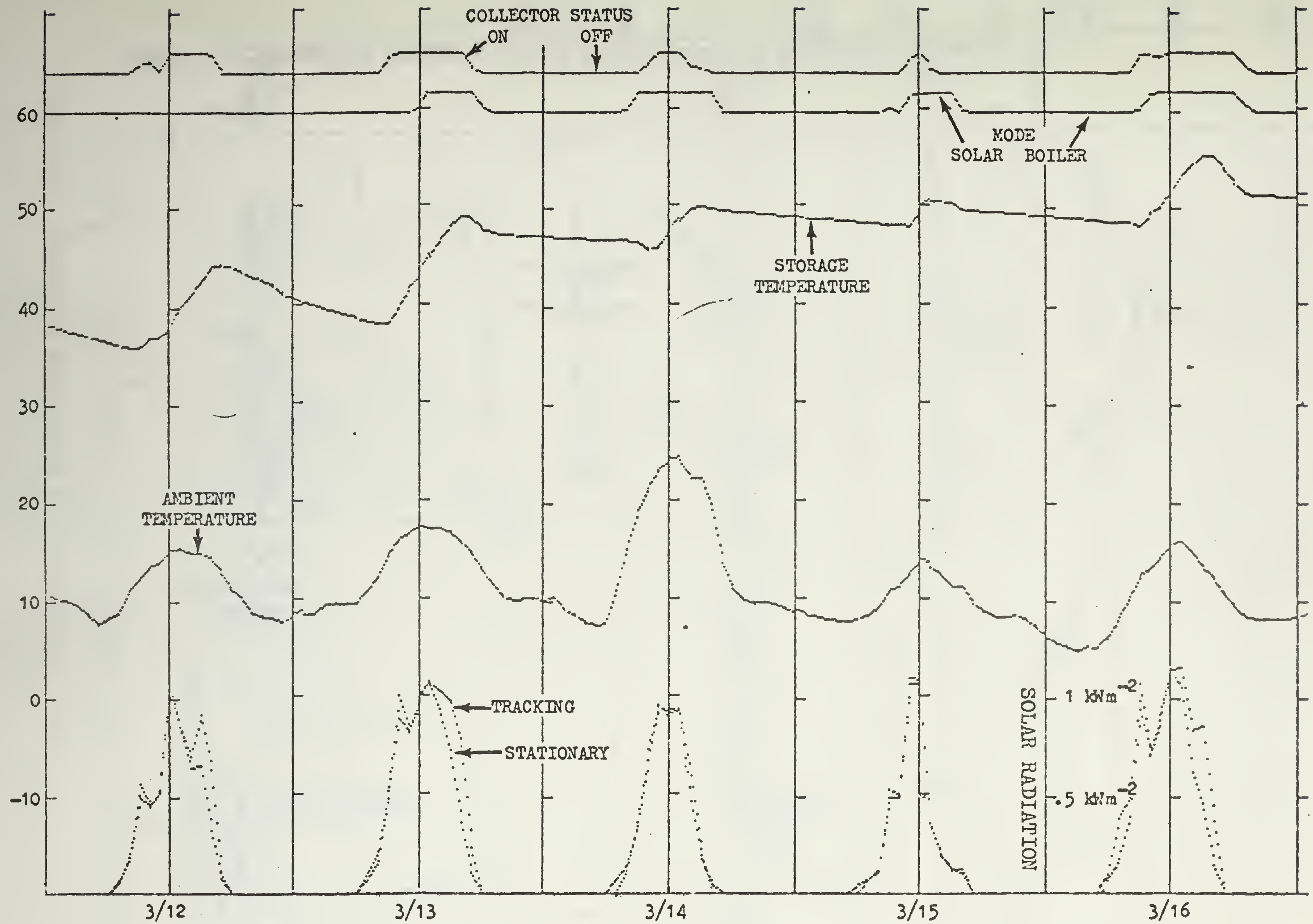


Figure 12: Graphical Presentation of Hourly Data for Five Days in March

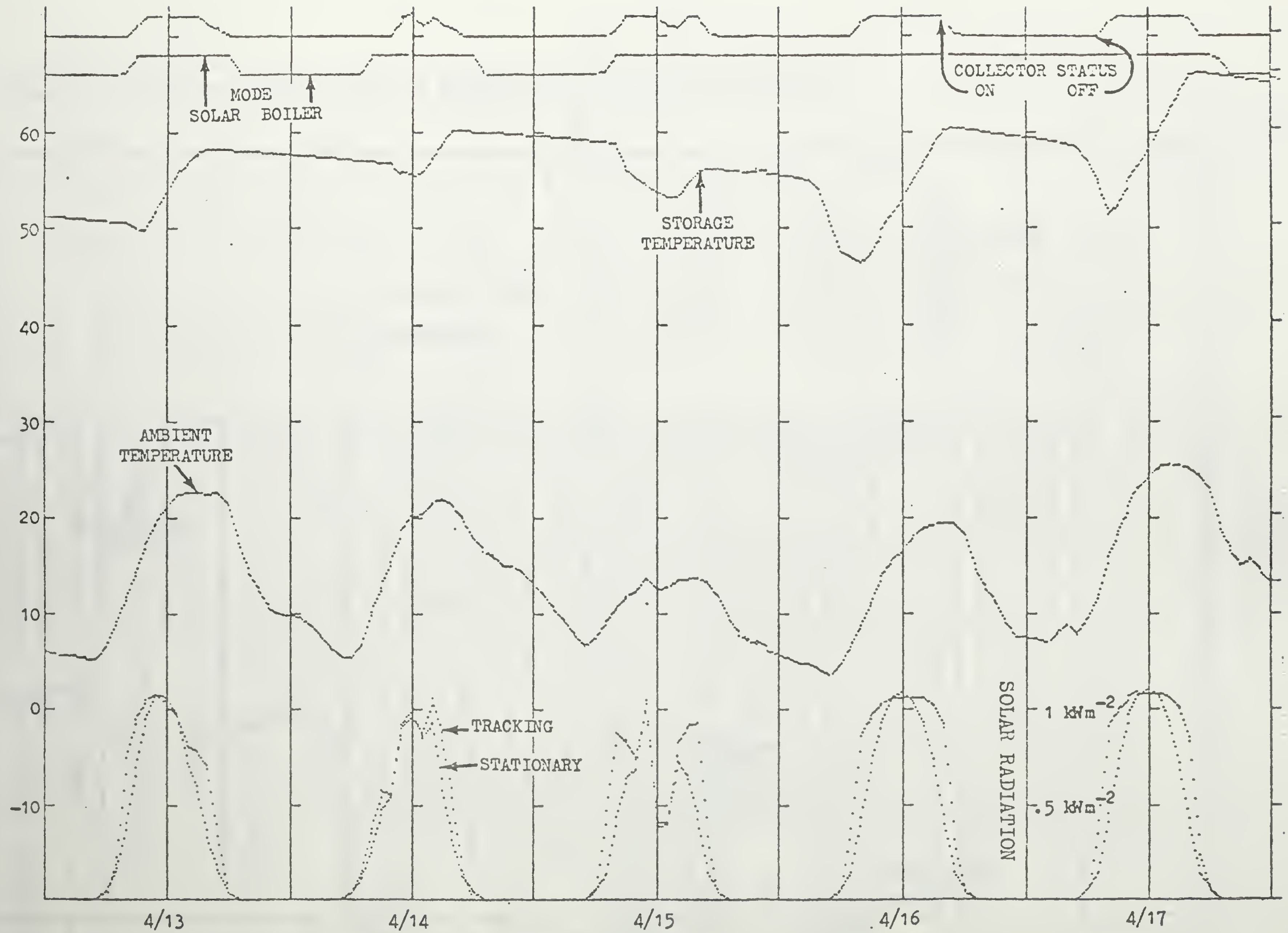


Figure 13: Graphical Presentation of Hourly Data for Five Days in April

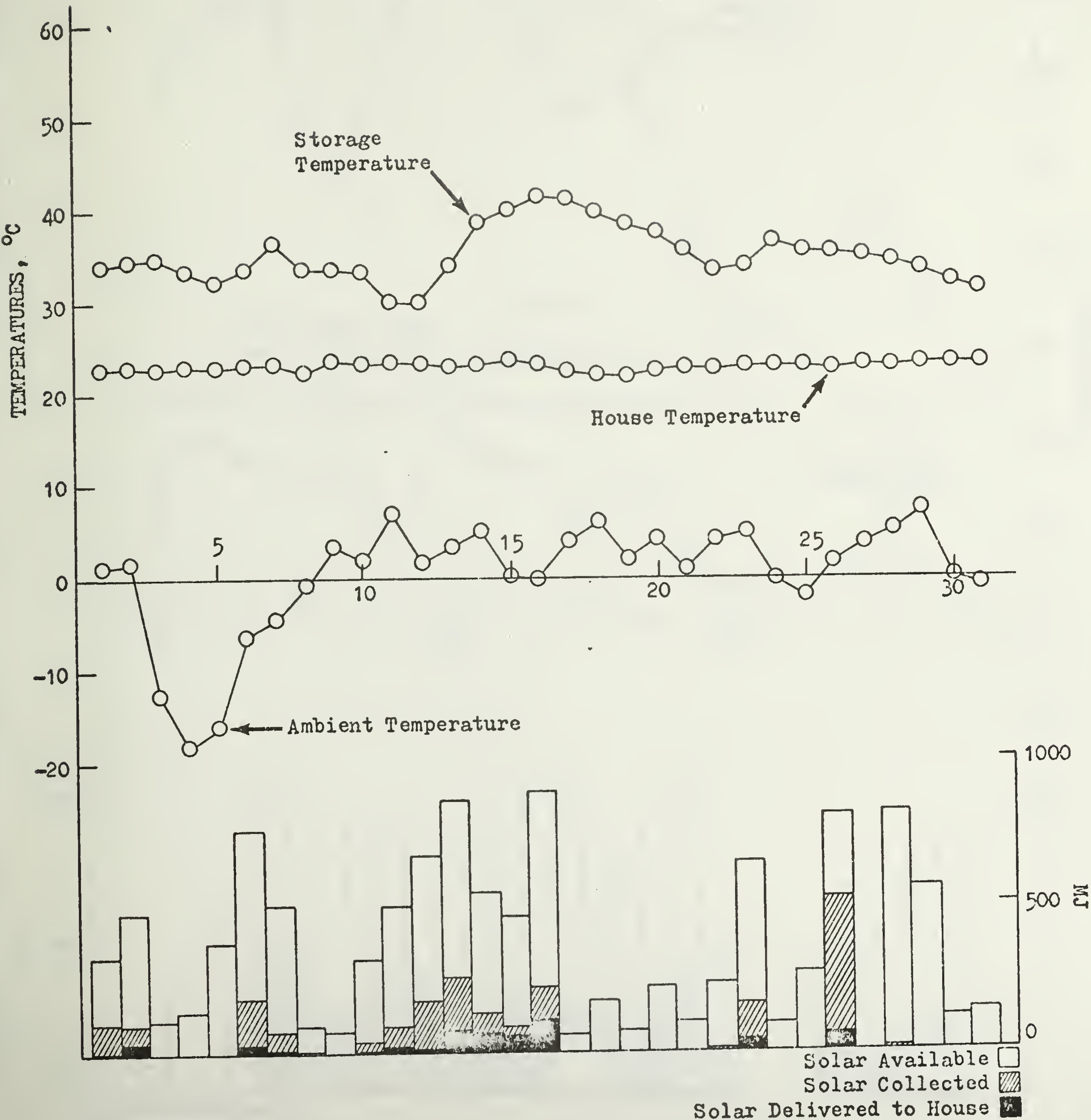


Figure 14: Graphs of Daily Data for the Month of March

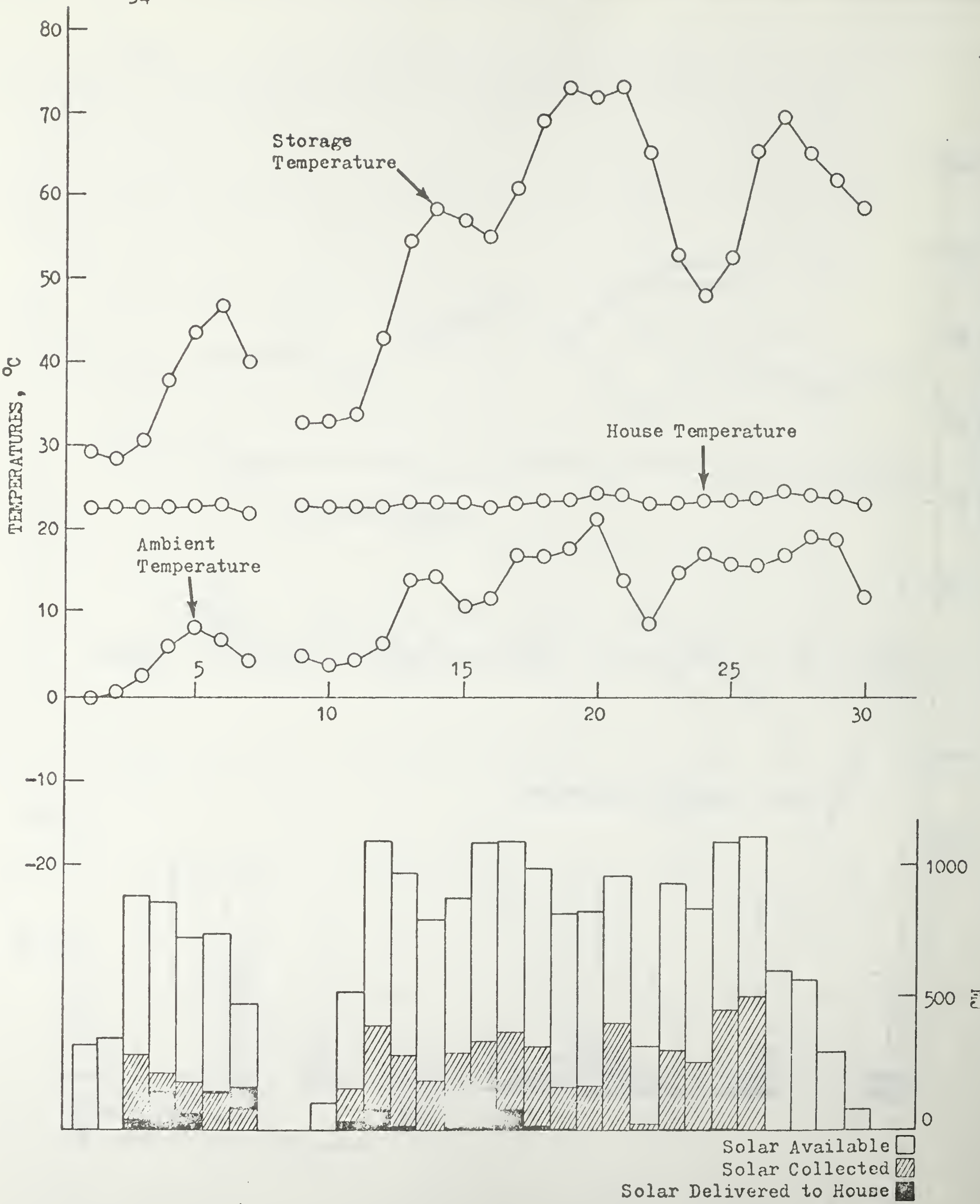


Figure 15: Graphs of Daily Data for the Month of April

APPENDIX I

TABLES OF HOURLY PERFORMANCE DATA FOR KILBY HOUSE

```
500 REM *** CALCULATE HOURLY DATA ***
505 IF V(1)<.02 THEN V(1)-0
510 S(1)-V(3)*.96\IF S(1)<0 THEN S(1)-0\REM SOLAR INSOLATION
515 S(2)-V(1)*29.7*3.6*.96\REM SOLAR INPUT
517 IF M>3 AND R>295 THEN F6-.75 ELSE F6-1
520 S(3)-(V(8)+V(35))/2*F6\REM COLLECTOR OUTPUT
525 S(4)-V(12)*.25*(2+V(19)-V(20))\REM SOLAR INTO DHW EXCHANGER
530 S(9)-.91*(V(29)-V(30))\REM CALCULATED HOUSE LOAD
535 S(6)-V(14)*V(6)*.026*V(27)\REM CALC SOLAR TO HOUSE
540 S(7)-V(14)*(1-V(6))*.026*V(27)\REM CALC AUXILIARY TO HOUSE
567 IF V(22)>30 THEN V(22)-27.7\REM MECHANICAL ROOM CORRECTION
568 S(8)-S(6)+S(7)+5\REM SUMM INPUT
569 S(15)-(V(22)-V(38))/24\REM STORAGE LOSS
570 S(16)-V(2)*3.6\REM AUXILLARY POWER
572 S(5)-S(3)-S(4)-S(6)\REM SOLAR INTO STORAGE
575 S(10)-V(22)\REM MECHANICAL ROOM TEMPERATURE
585 S(11)-V(38)\REM STORAGE TEMP
590 S(12)-V(30)\REM AMBIENT TEMP
595 S(13)-V(29)\REM HOUSTEMP
596 IF F9-0 THEN F9-V(39)\REM FIRST RUN TRAP
597 S(14)-(V(38)-F9)*15.85\REM DELTA STORAGE
598 F9-V(38)\REM PREVIOUS HOUR VALUE
```

EQUATIONS USED TO PROCESS DATA

DAILY PERFORMANCE SUMMARY FOR THE KILBY HOUSE 3/ 2/80

HR	SOLAR INSOL (KWM-2)	SOLAR INPUT (MJ)	COLL OUTPUT (MJ)	SOLAR DHWX (MJ)	SOLAR STORE (MJ)	SOLAR HOUSE (MJ)	AUX HOUSE (MJ)	SUN INPUT (MJ)	HOUSE LOAD (MJ)	MECH ROOM (C)	STORE TEMP (C)	AMBT TEMP (C)	HOUSE TEMP (C)	DELTA STORE (MJ)	STORE LOSS (MJ)	AUX POWER (MJ)
1	.0	.0	.0	.0	.0	.0	11.3	16.3	24.1	16.6	34.2	-3.9	22.5	-.9	-.7	.0
2	.0	.0	.0	.0	.0	.0	20.1	25.1	24.4	16.7	34.2	-4.4	22.4	-1.1	-.7	.0
3	.0	.0	.0	.0	.0	.0	15.4	20.4	24.7	16.6	34.1	-4.7	22.5	-.7	-.7	.0
4	.0	.0	.0	.0	.0	.0	18.4	23.4	24.8	16.7	34.1	-4.7	22.6	-1.0	-.7	.0
5	.0	.0	.0	.0	.0	.0	19.1	24.1	24.1	16.6	34.0	-4.0	22.6	-.5	-.7	.0
6	.0	.0	.0	.0	.0	.0	19.2	24.2	22.2	16.6	34.0	-1.8	22.6	-.9	-.7	.0
7	.0	.0	.0	.0	.0	.0	14.6	19.6	19.3	16.5	33.9	1.2	22.4	-.6	-.7	.0
8	.0	2.1	.0	.0	.0	.0	20.4	25.4	17.9	16.2	33.9	3.0	22.6	-.9	-.7	.0
9	.1	6.2	.0	.0	.0	.0	12.6	17.6	17.1	16.6	33.8	3.7	22.6	-.5	-.7	.0
10	.2	14.4	.0	.5	-.5	.0	11.8	16.8	15.4	16.3	33.8	5.6	22.5	-.9	-.7	.1
11	.2	24.6	.0	7.8	-7.8	.0	15.1	20.1	14.1	16.6	33.7	7.1	22.6	-2.0	-.7	.8
12	.3	33.9	.0	7.7	-7.7	.0	10.8	15.8	13.5	16.5	33.2	7.8	22.6	-7.9	-.7	.6
13	.5	52.3	.0	6.8	-6.8	.0	3.5	8.5	13.0	16.7	31.6	8.4	22.7	-24.4	-.6	.7
14	1.0	105.7	35.7	6.3	27.3	2.1	5.9	13.0	11.5	18.3	32.0	10.4	23.1	5.5	-.6	2.1
15	.7	83.3	30.1	5.2	22.1	2.8	.0	7.8	11.6	20.1	33.9	10.2	22.9	30.7	-.6	2.1
16	.5	70.8	18.4	4.2	8.8	5.4	.0	10.4	12.2	20.1	34.4	9.5	22.9	8.0	-.6	1.4
17	.4	66.7	20.1	3.3	11.7	5.1	.0	10.1	13.2	20.8	35.2	8.2	22.7	13.1	-.6	2.0
18	.1	5.1	.0	1.5	-3.3	1.8	7.7	14.5	16.6	20.5	35.4	4.6	22.8	2.2	-.6	.8
19	.0	.0	.0	.1	-.4	.3	11.2	16.5	19.0	20.0	35.3	2.0	22.9	-1.1	-.6	.1
20	.0	.0	.0	.0	.0	.0	6.0	11.0	20.1	19.3	35.2	.7	22.8	-.9	-.7	.0
21	.0	.0	.0	.0	.0	.0	7.6	12.6	21.2	18.8	35.2	-.7	22.6	-.9	-.7	.0
22	.0	.0	.0	.0	.0	.0	10.6	15.6	23.7	18.3	35.1	-3.4	22.6	-1.2	-.7	.0
23	.0	.0	.0	.0	.0	.0	10.0	15.0	25.8	17.8	35.0	-6.0	22.3	-1.3	-.7	.0
0	.0	.0	.0	.0	.0	.0	11.1	16.1	27.0	17.3	35.0	-7.3	22.4	-1.1	-.7	.0
	4.4	470.1	104.2	43.3	43.4	17.5	262.5	400.0	456.4	17.8	34.2	1.7	22.6	10.6	-16.4	10.8

APPENDIX II

DATA ACQUISITION SYSTEM

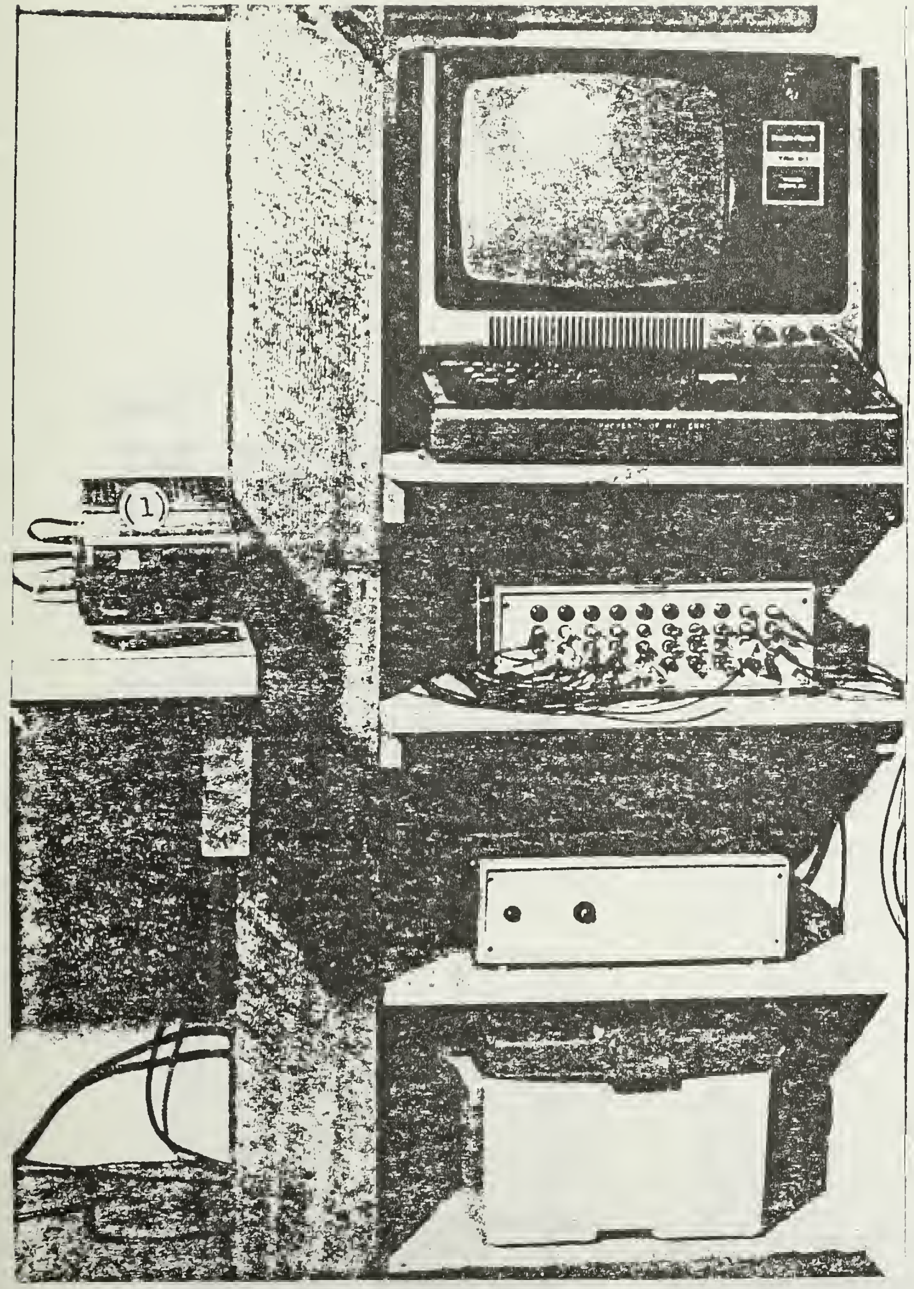
A low cost data acquisition system was developed for solar performance monitoring and is pictured in Figure 1 on the following page. The heart of the system is a Radio Shack TRS-80 computer having a 4K memory. This system has the capability of 40 input channels and is controlled by a Level II BASIC program which allows the user to structure data sampling and processing procedures. Calibration constants, error checks, scan rate, data averaging, printing, etc., can be manipulated using this program capability. A real time clock within the A/D converter chassis is used to time the data output on the cassette. Scanning at an average rate of 40 channels per five seconds, the data is averaged at the end of each hour. This data is then written onto the cassette recorder for processing at a later time.

Temperatures were measured using AD-590 transducers made by Analog Devices. A BASIC computer program was used with the data acquisition system to calibrate the probes against a precision thermometer. The absolute accuracy of the temperatures measured is better than 0.5°C (1°F), while the accuracy of small temperature differences is 0.1°C (0.18°F).

Total solar radiation on the collector surface was measured using a silicon cell pyranometer. The device was manufactured by the contractor and is mounted in the plane of the solar collector. The device has been referenced to NOAA Standards with an estimated overall accuracy of 5%.

Electric power is measured using clamp-on ammeters calibrated on-site against the utility kWh meter. The status of motors, dampers, curtains and fans is determined using appropriate relays, microswitches or mercury switches.

Flow in liquid systems is measured using Hersey MVR-30 turbine meters which have been interfaced to the DAS. Flow in air systems is mapped using a hot-wire anemometer for a one-time measurement to characterize the flow. Status switches and software combine the one-time measurements to calculate appropriate heat flow quantities.



— Video display of current data scan: 40 channels, time, date

— Keyboard for controlling system

(1) Cassette for storing data and programs

— 40 channels analog input, A/D conversion (12 bit), real time clock

— Power supply for computer and A/D interface

— 12V battery: powers system up to 5 hours in the event of a power shortage

Figure 1: Computer-Based Data Acquisition System

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EXPERIMENTAL PROBLEMS IN MEASURING THE THERMAL PERFORMANCE OF PASSIVE SOLAR SYSTEMS

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ABSTRACT

This paper discusses experimental problems and techniques associated with measuring the thermal performance of passive solar heated houses. Sample data from three projects is presented to illustrate important features of the houses and to demonstrate the methods used to reduce experimental error.

1.0 INTRODUCTION

During the past two years we have monitored the performance of twelve solar heated projects in Montana. Three of these projects used passive solar heating: (a) a water-wall residence, Figure 1; (b) an earth sheltered, sun-space residence, Figure 2; (c) an earth-sheltered, passive greenhouse, Figure 3. Each of these projects was monitored for two to three months during the winter.

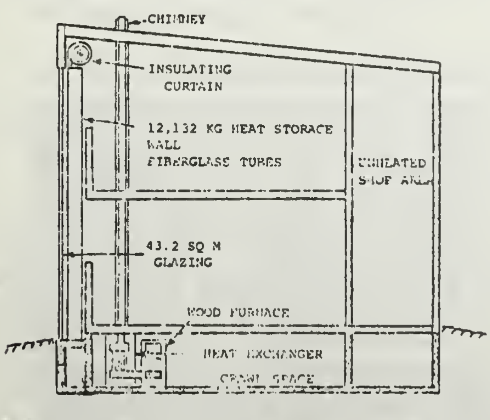

Fig. 1: Water wall system in residence

Data typically consisted of around 20 channels of information including solar insolation, electric power, auxiliary power and many temperatures. The data acquisition system utilized a Radio Shack TRS-80 microcomputer having an A/D interface and a real time clock. The system sampled all channels about 600 times each hour and stored hourly averages on cassette tape. The resolution of temperature measurement was 0.1°C.

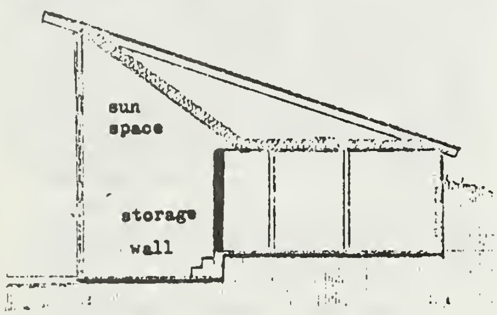

Fig. 2: Sun-space design, earth sheltered

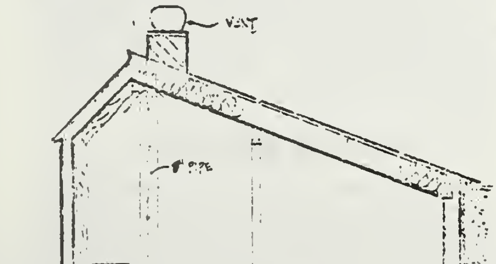

Fig. 3: Earth-sheltered greenhouse

2.0 HEAT BALANCE CALCULATIONS

Heat balance calculations provide the final gauge of accuracy in a performance monitoring project. The heat balance equation along with typical components are shown on the following page.

INPUT ENERGY	- STORED ENERGY	= OUTPUT ENERGY
Solar Gain	Passive Wall	Conduction
Aux. Furnace	Slab	Infiltration
Incid. Elect.	Structure	Convection
Wood Stove	Contents	Radiation

We typically try to measure everything on the left-hand side of the equation. The output term on the right is determined from a calculated heat load factor and measured inside-ambient temperature difference.

In each project there are some items in the heat balance equation that are well known while other items have greater uncertainty. The main task of analyzing the data is to use the heat balance requirement to identify, quantify and reduce (if possible) the error in the individual items.

The heat balance is evaluated in three time frames: (a) hourly average, (b) daily average and (c) monthly average. In the monthly time frame, the storage terms of the equation are nearly zero. This allows a test of the sum of the inputs against the calculated loss. If there are discrepancies in the balance, a study of the daily and hourly heat balances will usually identify the term(s) causing the unbalance. There are always sub-sets of the data where one or more of the inputs are zero or small; for example, cloudy days when the solar input was near zero, warm days when auxiliary heat was near zero, days when the wood stove was not used, etc. These sub-sets allow a heat balance test of the remaining items in the equation.

Our data analysis procedures consist mainly of repeated iterations of hourly, daily and monthly heat balances. Uncertain variables such as the heat output from a wood stove, heat loss coefficients of large insulated collector windows and heat storage in large masses are gradually defined using this process.

3.0 MEASURING THE ENERGY INPUTS

The solar energy input in the most simple case is the solar flux measured behind the window multiplied by the area of the window. If the solar flux is measured outside the window a factor for overall transmission must be used. A thermal pyranometer may be in error when tilted and a silicon cell radiometer may be in error if used behind the glazing. Some collectors are partially shaded by overhangs or trees and the resulting variable aperture must be accounted for in the analysis.

The interior shading due to movable insulation must be known. The status of the movable insulation can be sensed with switches, an inside solar transducer or temperature probes between the glazing and the curtain. We monitored one project where the movable insulation was in two independent sections. These sections were operated manually by the owner on a fluctuating schedule. Once we established the status of the insulating system we had to account for four possible conditions of heat loss and solar gain each hour!

The auxiliary furnace heat output is usually calculated from inlet and outlet temperature and flow rate measurements. Measuring air flow is often difficult due to short sections of duct, poor physical access and irregular flows. The accuracy of measuring the furnace output on the site may be only $\pm$ 10 percent.

Incidental electric input is due to heat from lighting and appliances. The on-site measurement is normally limited to total electric power entering the envelope. If the house has an electric water heater or clothes dryer, only a portion of the total electrical input is dissipated within the envelope. We use a factor between 0.6 and 0.8 for these houses. Incidental electric dissipation may account for 10 percent of the heating requirements so it cannot be ignored in the heat balance.

Many of our monitoring projects include wood stoves which provide 10 to 40 percent of the heat load. We do not know of an accurate and simple way to measure the output of a wood stove in situ. We approximate the stove output by measuring the temperature at a point close to the stove and subtracting the temperature of a point remote from the stove. This difference is multiplied by an empirical factor which is derived from the hourly heat balance data. This approach is clearly approximate but we have looked at several thousands of hourly heat balances which verify its utility.

4.0 MEASURING STORED ENERGY

Passive projects use large volumes of low-temperature storage mass. The heat exchanges between the house air, solar radiation and these storage elements is very complex and difficult to measure. The conceptual model we use for each storage element to calculate hourly heat balances is "an effective mass at a uniform temperature". The stored heat is then the temperature change per hour multiplied by the thermal mass. In practice the mass is usually not well defined (slabs, earth-contact concrete walls, etc.). The temperature measurements are practically limited to a small number of probes and the probes can often be mounted only on the surface of the thermal mass.

Passive storage walls may have a thermal capacity of 30 MJ/°C and underground concrete in an earth-sheltered house may have a thermal capacity of well over 100 MJ/°C. The hourly temperature change in these storage elements

is often much less than 1°C. This small temperature change places strict resolution requirements on the temperature measuring instrumentation. Our instrumentation uses a 12 bit A/D converter which results in a resolution of 0.1°C per bit. The data system, however, averages about 600 samples per hour which significantly increases the resolution. These averaged values are stored on the data tape to a resolution of 0.01°C. We think the effective resolution of the system is around 0.05°C which has proven adequate.

The effect of these limitations is to cause a phase lag in the hourly heat balances. After looking at a hundred or a thousand hourly data sets, these phase lags can usually be recognized and the analyst will feel comfortable with the accuracy of the data. More elaborate conceptual models which account for the transient storage lag do not appear justified at this time.

5.0 HEAT LOSS DETERMINATION

We have not made specific heat loss or infiltration measurements on the houses we have monitored. For heat loss we start with an ASHRAE calculation to determine a heat loss factor, $MJ\,^\circ C^{-1} hr^{-1}$. This factor is multiplied by the measured hourly temperature difference and the heat balance equation is evaluated over the entire data set. After looking at selected hourly balances and overall average balances, this factor is adjusted if necessary. (The ASHRAE factors are usually conservative by 10 to 20 percent.)

6.0 MOVABLE INSULATION PROBLEMS

We have spent a lot of time trying to figure out the thermal behavior of movable insulation systems on the apertures of our passive projects. As discussed previously, it is a non-trivial instrumentation problem to provide probes which sense the open, closed or intermediate status of the movable insulation. This status directly determines the solar heat entering the house (a large number). The heat loss coefficient of the house will also vary by a factor of 1.25 to 2, depending on the insulation status. Meaningful heat balances are impossible if the insulation status is not accurately known.

We always measure the temperature of the air between the movable insulation and the glazing (T_{space}). This has proven to be a final indicator of curtain status if other schemes will not work. This measurement also allows calculation of the effective heat transfer coefficient of the curtain using the equation:

$$U_{curtain} = \frac{T_{house} - T_{space}}{T_{space} - T_{ambient}} \times U_{glazing}$$

where $U_{glazing}$ is taken from a handbook. Table 1 summarizes effective U data for four different movable insulation systems. Systems A, C and D were insulated fabric shades and B was a foam panel system.

TABLE 1: MOVABLE INSULATION SUMMARY

System	Thickness	Design U	Measured U
	cm	$Wm^{-2}\,^\circ C^{-1}$	$Wm^{-2}\,^\circ C^{-1}$
A	15.0	0.28	1.12
B	7.6	0.43	5.6
C	3.8	0.94	3.24
D	0.7	1.41	2.8

7.0 SAMPLE HOURLY DATA

Table 2 shows hourly energy balances and temperature data for the underground sun-space house. The UPPER and LOWER parts of the passive window are considered independently since these insulation systems are independent. On this sunny day only the upper insulation was removed. The air space of the lower insulation (LOWER CURT) got up to 78°C at 2 p.m. The analysis routine computed solar gain through the curtain and this is shown under LOWER SOLAR.

The PASS WALL, PASS SLAB and HOUSE MASS are the three storage elements that were instrumented; negative numbers indicate the storage element is absorbing heat. The HEAT PUMP and WOOD STOVE input show these hourly inputs.

The SUMM INPUT column is the algebraic sum of the first seven input and storage columns and comprises the left-hand side of the energy balance equation. CALC LOSS is the calculated house heat loss coefficient times the actual temperature difference. The remaining columns are temperatures of the storage elements, the house air at three locations, the insulating curtain air space. The last column is the heat pump electrical energy input. (The daily average C.O.P. was 2.44.)

Comparing the SUMM INPUT and CALC LOSS columns gives an hourly test of the heat balance. The hourly balances for this "complicated" day are remarkably close and the daily totals on the bottom line agree almost exactly. Typically, the daily total heat balance is $\pm$ 20 percent. The fluctuations in the hourly heat balances are due primarily to the HOUSE MASS term which results from multiplying temperature changes in the BACK WALL by 125 $MJ\,^\circ C^{-1}$. These temperature changes are only hundredths of a degree Celsius per hour. This data demonstrates the resolution, stability and sampling problems in dealing with large passive storage masses.

Table 3 lists some overall performance summary data for three passive projects which were each monitored for two to three months during

TABLE 2: SAMPLE HOURLY DATA AND DAILY TOTALS FOR SUN-SPACE DESIGN, 1/28/80

HR	UPPER SOLAR (MJ)	LOWER SOLAR (MJ)	PASS WALL (MJ)	PASS SLAB (MJ)	HOUSE MASS (MJ)	HEAT PUMP (MJ)	WOOD STOVE (MJ)	SUMM INPUT (MJ)	CALC LOSS (MJ)	PASS WALL (C)	PASS SLAB (C)	BACK WALL (C)	SUN SPACE (C)	REAR TEMP (C)	HOUSE TEMP (C)	UPPER CURT (C)	LOWER CURT (C)	AMBT TEMP (C)	HEAT PUMP (MJ)	
1	.0	.0	2.0	1.9	2.5	.0	19.5	25.9	23.4	21.52	17.97	13.65	20.1	16.6	18.4	-4.7	5.2	-26.7	.0	
2	.0	.0	1.9	1.7	3.8	.0	18.4	25.7	23.1	21.14	17.81	13.63	19.2	16.3	17.8	-5.5	4.6	-26.8	.0	
3	.0	.0	2.0	1.7	5.0	.0	19.5	23.2	23.2	20.74	17.65	13.60	19.3	16.1	17.7	-5.9	4.3	-27.1	.0	
4	.0	.0	1.8	1.9	10.0	.0	19.2	32.9	23.4	20.38	17.47	13.56	18.9	15.9	17.4	-6.2	3.9	-27.6	.0	
5	.0	.0	2.0	1.7	10.0	.0	17.8	31.5	23.3	19.99	17.31	13.48	18.0	15.4	16.7	-6.6	3.6	-28.2	.0	
6	.0	.0	1.8	2.4	-6.3	.0	21.5	19.3	23.5	19.64	17.09	13.40	18.5	15.2	16.9	-6.7	3.2	-28.3	.0	
7	.0	.0	1.0	.4	1.3	8.9	30.9	42.3	29.0	19.45	17.05	13.45	20.3	15.9	18.1	-5.9	3.1	-28.0	3.5	
8	.0	.0	-.1	.2	3.8	.5	20.9	25.2	27.2	19.47	17.03	13.44	20.6	15.7	18.1	13.1	5.3	-28.2	.4	
9	15.1	.0	-1.3	-.1	-5.0	.0	18.3	27.0	27.6	19.72	17.04	13.41	23.2	16.0	19.6	24.4	22.5	-26.5	.0	U
10	28.1	6.3	-7.9	-3.2	-11.3	.0	17.9	30.0	26.2	21.30	17.34	13.45	25.0	17.6	21.3	31.6	42.4	-22.4	.0	U
11	36.9	11.8	-11.8	-3.0	-12.5	.0	17.7	39.1	25.4	23.65	17.62	13.54	26.7	18.7	22.7	33.8	58.9	-19.7	.0	U
12	42.0	14.8	-15.7	-3.2	-16.3	.0	.0	21.6	25.0	26.79	17.92	13.64	23.7	19.8	24.2	33.0	69.0	-17.5	.0	U
13	42.4	16.3	-15.9	-3.2	-8.8	.0	.0	30.9	24.9	29.96	18.22	13.77	30.0	20.6	25.3	32.3	74.6	-16.2	.0	U
14	39.9	17.4	-11.7	-2.6	-12.5	.0	.0	30.5	24.8	32.29	18.46	13.84	30.8	21.1	25.9	33.1	78.2	-15.4	.0	U
15	33.2	16.6	-5.2	-2.2	-6.3	.0	.0	36.2	24.8	33.33	18.66	13.94	31.0	21.3	26.1	32.6	76.4	-15.2	.0	U
16	22.2	13.5	-1.6	-1.6	.0	.0	.0	32.5	24.8	33.65	18.81	13.99	27.7	21.3	25.5	30.5	66.5	-15.8	.0	U
17	7.1	6.8	5.0	-.4	5.0	.0	.0	23.5	24.7	32.65	18.85	13.99	26.7	20.2	23.4	26.1	45.2	-17.7	.0	U
18	.0	.0	12.6	1.4	-1.3	.0	.0	12.7	23.8	30.13	18.72	13.95	22.8	18.7	20.7	18.1	23.5	-20.4	.0	U
19	.0	.0	9.3	1.3	-1.3	.0	10.2	19.5	27.6	28.23	18.60	13.96	23.8	18.7	21.2	7.5	17.9	-22.5	.0	
20	.0	.0	5.9	1.3	10.0	.0	11.5	23.7	27.8	27.10	18.48	13.97	23.5	18.5	21.0	3.5	14.1	-23.2	.0	
21	.0	.0	4.9	1.7	6.3	.0	11.5	24.4	23.2	26.12	18.32	13.87	22.6	18.1	20.3	.8	11.2	-24.4	.0	
22	.0	.0	4.9	2.2	1.3	.0	11.3	19.6	23.2	25.14	18.12	13.84	21.6	17.6	19.6	-.9	9.3	-25.2	.0	
23	.0	.0	4.3	2.0	5.0	.0	11.8	23.1	23.5	24.23	17.93	13.83	21.2	17.2	19.2	-2.2	7.9	-26.1	.0	
0	.0	.0	3.4	1.7	5.0	.0	13.2	23.3	27.0	23.60	17.77	13.79	21.4	17.0	19.2	-2.7	7.0	-26.8	.0	
	267.0	103.5	-8.5	4.1	-12.5	9.3	270.8	653.8	654.4	25.0	17.9	13.7	23.5	17.9	20.7	11.4	27.4	-23.2	3.8	

mid-winter. The storage mass has been categorized to show how much storage was exposed to direct solar radiation. Note that the ratio of aperture area to direct storage mass has a close relation to the temperature swing in the building. The temperature swings of the sun-space house and the greenhouse have been given for both the front (sun-space) and the rear of the house because these differ by large amounts. (Temperature swing is daily maximum minus daily minimum temperature.) The table also shows building heat loss coefficients with the movable insulation in place (closed) and removed (open). These differences are significant which points to the importance of efficient management of the movable insulation to reach high solar fractions. The greenhouse has no supplementary heat so the solar fraction was 1.0 by definition. The temperatures, however, dropped below freezing. If the temperatures had been maintained to an average 20°C the solar fraction would have been 0.75.

8.0 SUMMARY

(1) For solar performance monitoring the data acquisition system must be smart enough to do some processing and averaging on-line to capture transient events while at the same time condensing the output data. A sample rate of 600/hour and an output of once each hour seems about right for many projects. The required temperature resolution and accuracy is at least 0.1°C for collector $\triangle T$ and for the $\triangle T$ per hour of large, passive storage masses.

(2) The installation of the transducers requires considerable finesse and should be done or supervised by someone having a grasp of the overall project. Judgment is needed because of practical limitations on the number of transducer locations. There is normally no backup instrumentation so that if one channel of data is lost the project may be lost. The probes must be carefully installed and the raw data must be inspected as it is produced.

(3) The project is not finished when the raw data is dumped into tables. Considerable interpretation, data processing, cross-checking and common sense must be applied to the data before general conclusions can be drawn. For each month of hourly data we spend nearly a month in processing, interpretation and reporting. We have found that an hourly and daily heat balance is the best way to verify the data. The heat balance can identify errors in the data and in some cases points to ways to correct the data.

(4) The TRS-80 based data acquisition systems have performed satisfactorily. The flexibility allowed by LEVEL II BASIC and the low cost of the system are its main advantages. We have used three of these systems almost continuously during the past eighteen months.

TABLE 3: PERFORMANCE SUMMARY FOR THREE PASSIVE PROJECTS

		Water Wall	Sun-space	Greenhouse
Solar Aperture Area (m^2)		45	33	40
Floor Area (m^2)		210	113	74
Direct Storage (MJ^oC^{-1})		52	15	14
Indirect Storage (MJ^oC^{-1})		8	125	80
Heat Loss Factor:	Open Insulation	1.10	0.80	0.86
($MJ\ hr^{-1} {}^oC^{-1}$)	Average	0.85	0.69	0.63
	Closed Insulation	0.75	0.63	0.43
Solar Fraction		0.66	0.50	1.0
Average Interior Temperature, °C		19	20	14
Average Ambient Temperature, °C		-11	- 7.3	- 6.7
Temperature Swing: (°C)	$\frac{\text{Front}}{\text{Rear}}$, Average	6.4	$\frac{13.5}{5.9}$	$\frac{20.8}{14.9}$
	$\frac{\text{Front}}{\text{Rear}}$, Clear Day	8.5	$\frac{19.0}{11.5}$	$\frac{30.0}{22.0}$
Aperture Area/Floor Area		0.21	0.29	0.54
Aperture Area/Heat Loss Factor		52	57	67
Aperture Area/Direct Storage		0.85	2.2	2.9

(5) The actual heat loss coefficient of four movable insulation systems we have measured are far greater than the design values. The actual loss averages four times the design loss (Table 1)!

(6) The owners of the houses have cooperated with the monitoring effort and are interested in the data. The owners or designers seldom have an accurate idea of how well the system really works.

9.0 ACKNOWLEDGMENTS

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